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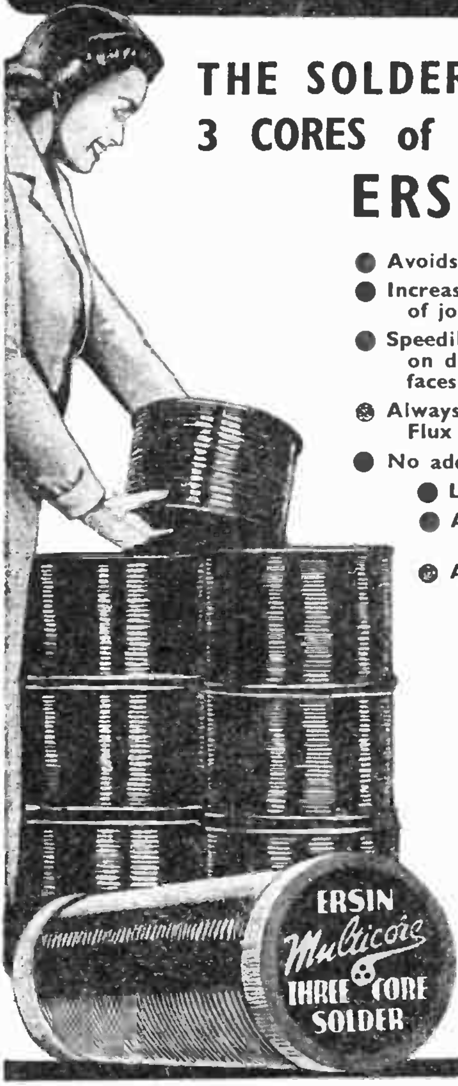
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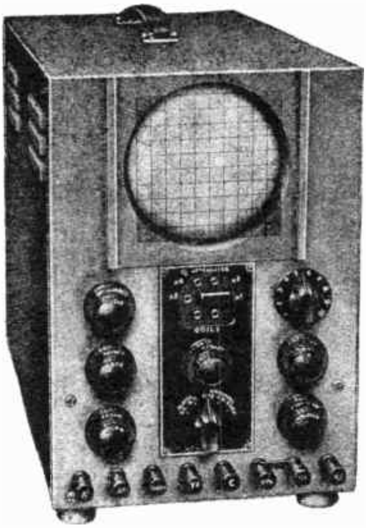

JOURNAL OF
The
British Institution of Radio Engineers
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NOVEMBER, 1943-FEBRUARY, 1944.

"To promote the general advancement of and to facilitate the exchange of information and ideas on Radio Science."

RADIO DEVELOPMENT IN AUSTRALIA

by

Sir Ernest Fisk (*Hon. Member*).*

(*Immediate Past President, Australian Institution of Radio Engineers.*)

(*A paper read before the Institution in London on September 3rd*, 1943.)

The PRESIDENT (Sir Louis Sterling), introducing Sir Ernest, said it was indeed a privilege to welcome him and to thank him for having agreed at very short notice to address the members of the Institution. Sir Stafford Cripps (Minister of Aircraft Production) had promised to address the meeting, but, owing to his war-time duties, he had found it quite impossible to attend. That was a great misfortune. On the other hand, the Institution had been extremely fortunate in the fact that Sir Ernest Fisk had arrived in this country only a few days before the meeting, and had very generously agreed to address the Institution on the occasion of the Annual General Meeting.

Those who have been engaged in radio activities for any length of time know of Sir Ernest as one of the pioneers of the industry, both scientifically and commercially. He was also the founder and first President of the oldest radio institution in the British Empire—the Australian Institution of Radio Engineers. The meeting was indeed fortunate in having the opportunity to welcome an Empire radio pioneer of such eminence.

Sir ERNEST FISK: It is indeed a pleasure and a privilege to address members of the British Institution, for it affords an opportunity to extend the greetings of the Australian Institution of Radio Engineers; the people of Australia are 97 per cent. British, and if

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* See Notices, page 325.

only for that reason all the members of the Australian Institution of Radio Engineers would support the greetings offered to the British Institution.

One of the reasons for Australia's early and continued interest in the development of radio communication was that the Australian Continent covered a vast area of three million square miles—just about the area of the United States of America—and was more or less isolated from the rest of the British Empire. Where distances were so great, communication became of the first importance, and it was realised that radio must play a great part in the development of communications in the future.

From as early as 1899 a few engineers and physicists had been experimenting with wireless in Australia; in 1905 Marconi sent two engineers (Dowsett and Denham) from Great Britain to give the first demonstration of practical wireless communication in Australia. They built one station on the southern coast of Victoria, about a hundred miles from the City of Melbourne, and another on the other side of the Bass Strait at Devonport on the northern coast of Tasmania; communication was then established between those two stations, a distance of about 180 miles. The transmitting equipment consisted of a 10-inch spark coil; the receiving apparatus was a coherer receiver and a Morse inker. Nevertheless, very effective communication was established.

Five years later the Commonwealth Parliament, which was then only 10 years old, passed an Act to regulate wireless telegraphy, as it was then called; that was probably one of the earliest wireless telegraph Acts passed in any country. Almost immediately the Government set out to develop wireless communication. In the following year (1911) John Graham Balsillie, who was then well known in the radio world, went from this country to Australia and set about establishing wireless communication stations round the coast to communicate with ships at sea. The first station was a temporary one, situated on one of the hotels in Sydney. Shortly afterwards a large station was established at Sydney, having a range of 1,200 miles, which at that time was regarded as extreme. That marked the beginning of wireless communication in Australia.

At about the same time the Marconi Company, from Great Britain, set up depots and commenced to equip ships; and two years later (1913) the manufacture of wireless apparatus was commenced in Sydney. Thus, Australia has been a wireless apparatus manufacturing country for thirty years. Apparatus for ships, for the Army and for land stations was manufactured in Australia throughout the war of 1914-18; some of it was shipped to China, Japan, East Africa and to many of the islands in the Pacific Ocean.

Towards the end of the war of 1914-18 a few people in Australia discussed with Marconi the possibility of communicating direct by wireless between that Continent and Great Britain; there were others, some of them quite eminent in the scientific world, who had explained how and why that was impossible and would always remain impossible. In September, 1918, however, Marconi sent some messages from his trans-Atlantic station at Caernarvon in Wales, and they were clearly received at an experimental station at Wahroonge, near Sydney ; thus the possibilities of direct wireless communication between Australia and Great Britain were demonstrated.

Following that experiment, some people in Australia and in Great Britain proposed the establishment of a regular service of communication by wireless telegraphy between the two countries. Some difficulties were raised by public Departments, and eighteen months later an alternative scheme was propounded to establish communication between Great Britain and Australia by sending messages from Great Britain to Cairo, from Cairo to Baghdad, and thence to Poona, to Singapore and to Port Darwin. Unfortunately, however, Port Darwin was 2,000 miles distant from Sydney and about 2,500 miles from Melbourne, and most Australian business was transacted from one of those two cities. Port Darwin was about 1,500 miles distant from Perth and 1,800 miles from Brisbane. Thus, the advocates of direct communication did not view the proposed alternative scheme with satisfaction because one of the basic advantages of wireless communication was supposed to be rapidity. A message would be sent from Great Britain to Cairo, where messages would also be received for Africa, Mesopotamia and other Eastern places. Those Australian messages would be sent on to Baghdad together with others for Poona, Singapore and Port Darwin, so that the passage of any message to Port Darwin would not be very rapid, and one could not tell what might happen when it reached there.

The proposed scheme was not attractive from either the commercial or the strategic or defence points of view. Anything might happen at intermediate stations in the event of war.

Argument ensued until the Right Hon. W. M. Hughes, at that time Prime Minister of Australia, visited Great Britain in 1921 to attend an Imperial Conference. Whilst in this country he had travelled to Wales and had visited another Welshman, who happened also to be a Prime Minister ! As a result of their meeting it was arranged that there should be direct communication by wireless between Australia and Great Britain.

It was still necessary, however, to overcome resistance and inertia—two physical factors to which radio engineers were accustomed—and by 1924 the service had not been established. It was proposed to carry on the service by long waves of about 30,000 metres ! It was hoped to put 1,000 kW into an aerial supported over an area of a square mile on steel latticed masts 820 feet high. That was quite an ambitious project, and the people responsible for it had very good reason to believe that they could carry it out ; indeed, they offered to guarantee to transmit a minimum of 20 words per minute each way for 12 hours per day for an average of 300 days per annum. Experiments, which had been proceeding during the period from 1918 to 1922, led them to believe that it was practicable. But there was still a lot of resistance, and the project did not materialise.

In 1924, Marconi, who had been experimenting since 1922 with beam transmission between Hendon and Birmingham, decided that on short waves he would try to use the beam for communication over greater distances ; and from his yacht he established communication down to the Azores. Becoming more ambitious he cabled and asked me to listen in Sydney for the short-wave signals. I established another experimental station, and when the sun was in the right position, received morse signals remarkably well from Marconi's short-wave station in England.

Shortly after that, Marconi used a microphone at his experimental hut in Cornwall, and spoke to me in Sydney ; that was the first occasion on which the sound of the human voice was transmitted from this country to Australia ; the reception was so clear that I could detect the reverberations of the wooden hut from which Marconi was speaking.

Following that, the Marconi Company cabled to Australia to advise against the establishment of a high-powered long-wave station pointing out that the new beam system would entail very much less cost and would give a great deal more capacity. Accordingly, many of us who were interested in the work approached the Government to report against the use of a high-powered, long-wave station and in favour of the establishment of the short-wave beam station. The Ministers and many of the statesmen in the Australian Parliament had been looking forward to the establishmen of the long-wave station, with its 820-feet masts supporting an antenna over an area of a square mile, and there was naturally some disappointment when it was proposed to establish in its stead a comparatively small short-wave beam station. That was overcome ; but from other quarters there was a good deal of opposition. It was said that the promoters could not possibly establish a short-wave communication service between England and Australia, and that a service could be established only by means of a high-powered long-wave station. That was in 1924, only five years after it had been said that communication could not be established by a high-powered long-wave station.

The Government decided to go ahead, and the necessary Act was passed by Parliament. Three years later the service was opened, the work having proceeded fairly rapidly. The efficiency of that method of communication which rediscovered the ionosphere startled the world ; and since then short-wave directional communication has come to be used by all countries of the world.

It was a matter for pride that Great Britain and Australia had pioneered that very important system of radio communication. In 1928, only a year after the erection of the first station in Australia, a second station was erected there for short-wave transmission, the apparatus being arranged for voice transmission, i.e. for telephony.

In that year Australia had the privilege of broadcasting to Great Britain from one of the Sydney stations a programme which was picked up by the B.B.C. and relayed through the London stations. That transmission was made on Australia Day (January 26th) and was, I believe, the first world-range broadcast relay in history.

Two years later, the Australian internal telephone network was connected with the short-wave station there, and through the medium of an efficient station operated in Great Britain, by the Post Office, the internal telephone networks of Australia and Great Britain were connected. That was the first occasion on which the telephone networks of one of the Dominions and the Home Country had been connected.

Reverting to some of the outstanding events in the early developments of wireless communication in Australia, I recall that in 1913 a fair sized ship trading around the coasts of Australia was equipped with the Bellini-Tosi goniometer, and two stations were established on the coast for direction finding with ships at sea. Much later, about the year 1935, a vessel owned by the same company was equipped with a broadcasting station, using short waves. I believe that was the first and perhaps the only ship in the world to be equipped with a regular broadcast transmitting service.

A demonstration of the possibilities of broadcasting was given in Sydney at a meeting of the Royal Society of New South Wales in July, 1919. In October, 1920, a broadcast entertainment lasting an hour was given to 400 people assembled in the Queen's Hall, Federal Parliament House, Melbourne, transmitted from a station nine miles distant. In January, 1921, a regular broadcasting service, operating on four nights a week, was started from a small station in the City of Melbourne. But in respect of regularly organised broadcasting, Australia was behind the old country; the first service was opened in this country in November, 1922, at 2LO, whereas the first official regular broadcasting service in Australia was opened in Sydney in November, 1924.

Naturally, in the early stages of broadcasting there was a great deal of interest and much rivalry to establish broadcasting services. The only solution that could be found was to give each of those ambitious entertainers a wavelength and to allow the vendors of receiving sets to sell sets fitted for reception of the wavelengths to which the buyers subscribed. If a buyer subscribed to six broadcasting services he could buy a receiving set fitted for reception on the wavelengths of the particular services to which he subscribed.

Some problems developed in connection with the design of receiving apparatus, and they were overcome; but when it came to testing the receiving apparatus, the unfortunate people responsible for the testing threw up their hands and proclaimed that the system could not work. Thus, the system was thrown overboard, and from it there developed a haphazard scheme of commercial broadcasting. A few enthusiasts set up stations in their homes, and that state of affairs continued for about two years; then the Government decided that something on a larger scale was necessary, something rather on the lines of the B.B.C., and in due course a body was set up which became ultimately the Australian Broadcasting Commission. The Commission was responsible only for the provision of the programmes. It was appointed by the Government and consisted of quite a good selection of people possessing the required qualifications; they decided upon and directed the programme policy, to which the management gave effect.

The technical side of the national service was handled by the Australian Post Office, which provides and operates the technical equipment for all national service broadcasting stations and studios. A charge of £1 per annum is made for a listener's licence, 10s. being allocated to the programme side and 10s. to the technical side. Out of that there had developed a national broadcasting service which to-day operates 25 broadcasting stations covering the populated parts of Australia. Bearing in mind the nature of the territory and the lay-out of the population, quite a good service is afforded.

There are two branches of the service. One is known as the national service, where stations broadcast simultaneously to all the States; the other branch consists of the regional service, involving broadcasting to each State separately.

Side by side with that scheme there has grown up a commercial broadcasting service, using some 98 broadcasting stations situated throughout Australia. These stations are owned and operated by various companies and individuals, who cover their costs by advertising revenue.

Thus, there was the national service similar to that of the B.B.C., which must not advertise, as well as a commercial service run on similar lines to those of the American broadcasting system. Such an arrangement had proved to be a very good thing for a country such as Australia. Quite apart from practical reasons, there were political reasons for it. Undoubtedly in a new country, which had not the long political experience such as that of Great Britain, it was a good thing to establish means whereby the advocates of various political views could, if they had the money to meet the cost, present their views for the consideration of the public. That, of course, could not possibly be done through a national service, which must be impartial. It was a good thing also from the point of view of broadcasting generally. Australia had not the scope for talent such as existed in Great Britain or the United States, and if there were only one service there, whether it be the national or the commercial service, there would be probably a great deal of dissatisfaction. But with the two services, having an element of competition between them, the commercial stations being under various ownerships, the listeners enjoyed quite a wide variety of programmes. That had contributed largely to the popularity of broadcasting in Australia. There is supported opinion that the standard attained in the programmes was really quite high. As a result, among a population of 7.15 millions there were nearly 1½ million licensed listeners, so that there was an approach to saturation point in terms of the number of homes. Australia stood fairly high in the scale of listener densities covering the various countries. He believed that the United States was first, Denmark was usually second and Australia occupied the fourth or fifth place. That indicated that the services in Australia were giving a reasonable degree of satisfaction to the public; any service, offering anything to the public, must be assessed first by its public acceptance.

Side by side with broadcasting development a very active and successful radio manufacturing industry had developed in Australia, so successful, that practically all the radio requirements in Australia were met by that industry. Before the present war Australian manufacturers were engaged mainly in the production of receiving sets, the market for which had varied from 150,000 to 250,000 per annum, giving the larger factories a reasonable output.

Development in the technical sense had also been successful. The communication and broadcasting stations were all designed and constructed by the Australian industry. From the point of view of technical standards and efficiency they compared quite favourably with the stations in other countries.

During this war the radio manufacturing industry had proved to be a valuable asset to Australia and to-day most of the radio factories employed two or three times as many workers as they did before the war. The largest factory employed more than 4,000 people; it was quite a sizeable factory for a country having a population of only 7,000,000 people, and the industry was making practically everything used in the radio field in modern warfare. That equipment was being made in very large quantities. Equipment was not only being supplied to the Australian and United States Forces, but to New Zealand, India and other countries. Indeed, some of the Australian radio products had been sent to Great Britain, not because of its quality—for there was no quality better than the British—but because at certain times they happened to be needed.

All that development proved that the people of Australia were radio-minded. The country had produced quite a number of well-trained technical, scientific and engineering people in the radio field, giving good scope to the Australian Institution of Radio Engineers.

Sir Louis Sterling referred to the Australian Institution as being the oldest radio institution in the Empire. The Wireless Institution of New South Wales, from which the Institution developed, was certainly the first wireless association of any kind formed within the British Empire, but it was not until 1924 that the Australian Institution of Radio Engineers, as such, was organised on the accepted lines of a professional body. To-day the Institution had more than 700 members, equivalent to about 4,500 in Great Britain and 14,000 or 15,000 in the United States. Assessed on the basis of population, the Australian Institution has a higher ratio of membership than any other radio institution of a similar nature. It is very active and is supported enthusiastically by all the engineers and technical people. Its policy, its objective and its ideals are substantially identical with those of the British Institution of Radio Engineers.

A grade of membership in the Australian Institution, which I believe has not its counterpart in the British Institution, was that of Companionship,* which was open to non-technical people who were actively engaged in radio work, such as the managers of broadcasting stations, members of the Australian Broadcasting Commission, and so on. The view was that the progress of the art could be assisted by securing the closest possible co-operation between the purely technical side and other people who were engaged in radio work. The Companions had most of the privileges of membership ; they could not serve on the Council, but they could attend meetings. It was hoped that some of the Companions would lecture to the technical people on matters concerning practical progress, financial problems, programme problems and general organisation, and that the technical and engineering members would lecture to the Companions on technical problems which impinged on the work of the latter. He believed the Institution could do a great deal of good work in that way.

Another class of membership which had been instituted—it was not exactly a grade—catered for those engaged in servicing many of whom would not be able to pass the examinations for the purely technical grades. They represented a very important part in making the engineers' work successful, and therefore they should be associated with the Institution. They were admitted after having completed various periods, ranging from three to six years of continuous work in servicing radio equipment ; their applications for admission, had, of course, to be supported by suitable credentials.

Apart from that, the technical standards of the Australian Institution were similar to those of the British Institution. I am not quite sure that in some of the newer fields the Australian standards were quite up to the British, but they were close to them. Examinations, which were frequent, were very rigid, and every care was taken in the grading of technical members.

Under war conditions there was considerable difficulty in obtaining technical papers and contributions because so many of the members were scattered abroad in the Forces, and the remainder were working long hours in the factories and the various Services.

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* See Institution Notices, page 325.

As President of the Australian Institution during the past two years, I have corresponded quite a lot with Sir Louis Sterling and Mr. Clifford on problems of co-operation between the two Institutions. Owing to war conditions, we have not been able to settle anything definitely, but we have agreed to the exchange of technical papers and matters of that kind, and there was mutual hope that there would be more and more association between the two Institutions—the British Institution might be regarded as the parent body because they had so much in common in their work, in addition to the fundamental factor that the members of both bodies were British. Moreover, the development of radio communication had a great contribution to make to the development of the British Empire. From time to time some people thought that the end of development in radio had arrived ; but as soon as that idea was accepted a new field of research opened. In the communication field an opinion existed at one time that the longer the range of transmission required the greater would be the power needed and hence the employment of a large antenna, and a long working wave length would be essential for satisfactory results. All this was based on the theory that only a long wave would go round the earth. The extremely high cost of the plant involved, however, caused engineers to reconsider these views, with the result you know ; a sudden change to the use of short waves followed eventually by development of the ultra-short wave technique.

Such developments were of the greatest importance to our Empire ; we were beginning to awaken to the fact that the future of the British Empire, the development of its physical resources and its defence, were greatly dependent upon the close association of all parts of the Empire ; and that association and co-operation must depend very largely on the efficiency of communications. We must develop our communications far more in the future than we have done in the past, and radio is the means by which they will be developed. By short-wave radio it is possible to provide a network of communications between all parts of the Empire, remote or proximate, as efficient as the internal communication system of the United States.

It is not suggested, of course, that the Empire communications system should constitute a closed circuit. There must also be efficient communication between other countries and the various parts of the Empire. Given an efficient communications network, we could link our broadcasting services with it at all points and to all points. That is an important job in which our radio institutions could properly take a lively interest.

There were also many other fields which were opening up. The British I.R.E. had wisely included the field of electronics within its scope, and one could not visualise the end of development in that field. It represented, not merely a new field of communication, not merely the taking of picture shows to every home, but a new field of electrical engineering which would probably enable us some day to dispense with revolving machinery, maybe even with humming transformers ! Looking not very far ahead, electrical engineering would be largely electronic. Thus, the scope of the Institutions in the future would be wider than at present ; and their membership figures should be astronomical.

Again, the electron theory presented an opportunity to experiment in radio-therapy, and the ultimate analysis of matter. Surely it was not too much to expect that, as the result of research and experiment, some day we should be dealing not merely with the thermal application of various frequencies to the human body, but something much more intimate in the technical sense, an intimate association between frequencies imposed by frequency-generating apparatus, and normal frequencies of the various parts, organs or atoms of the human body.

Another new development is that of the electron microscope, which I saw for the first time only a month ago in America.

Whilst I do not believe in the idea that the British people should set out to conquer the world in the field of electronics or in any other—although quite capable—they should hold their own and should not fall behind other countries in the development of research and the application of its results. We had always had our J. J. Thomsons and our Rutherfords, but frequently, after having carried out the fundamental research and pioneering, and having probably spent a lot of money on that work, we had left it to others to develop the practical applications and particularly the commercial exploitation. Particularly on the experimental and investigational sides the Institutions should watch developments and foster them as much as possible.

However, planning and scheming to make a better world, to build better houses, motor cars, and radio sets, even to produce better apples and pears, and so on, is rather unsatisfactory as an end in itself. The technical and scientific people could help to pass on to the lay public a better appreciation of the things they were working with and the meaning of those things, and perhaps by that means lead people to take a wider view of life ; it might be possible to lead people to the view that the solid things which we called " matter," properly analysed, are not solid at all, but comprise electron structures which, so far as we know, are entirely non-material ; and very likely some day we should be able to dispense with oscillating circuits and valves and things of that kind, and to communicate with each other directly. One is at least led to the speculation that man, in his ultimate analysis, is a spiritual rather than a material being. I believe that radio technique, radio art, radio science, are leading in that direction, and if that is so, then humanity can be given more hope, more purpose for living ; life could be made more worth while if we can lead up to a broader idea of the origin and the purpose of man, if not his destiny. If we do that we should be doing no more than to confirm, by rational means, what the various religious bodies have been trying to teach by emotional means. Some of the leading scientific men in this country are already talking along those lines ; and in that direction I believe that ultimately those who are working in the radio field have their most valuable contribution to make to the welfare of the human race.

Mr. Leslie McMichael (Vice-President), moving a vote of thanks to Sir Ernest Fisk for his interesting paper, said it was not generally realised that the Wireless Institute of New South Wales was definitely the first such body to be formed within the Empire, and probably the first in the world. During the early days of the Radio Society of Great Britain (formed in 1913 and of which Mr. McMichael was a Founder Member) information and ideas were exchanged with the New South Wales Institute.

Although Sir Enest had not said a great deal about the work of amateurs in Australia and in this country, he would no doubt agree that amateurs had carried out a very great deal of work which was of great value, particularly during the early days of short-wave transmission. Mr. McMichael mentioned particularly the work of men such as Gerald Marcuse and Simmonds, and their counterparts in Australia, and recalled that Marconi had always been among the first to give credit to them.

Seconding the proposal, **Dr. James Robinson** (Vice-President), stated that Sir Ernest Fisk had always been regarded as the spirit of radio in Australia and had been personally concerned with the developments which had led to the formation of the Amalgamated Wireless Co., Ltd.

In the manner of his address, and its contents, Sir Ernest was consistent with his own career. He was one of the body of pioneers around Marconi who had set out to convince the world that wireless signals were possible ; in other words, they had issued a challenge, for up to the time of Marconi's experiments communications had been established by means of wires only. The first development they introduced was to make wireless communication possible between ships and shore ; to-day's achievements in radio are developments of those early successes and continue to contribute to the safety of life.

When it was proposed to signal across oceans, scientists of the time stated that wireless waves could travel around the earth's surface only as far as light could be effective, and, therefore, it was absolutely impossible to signal across the Atlantic. But Marconi and his assistants proved that it could be done. Later, Sir Ernest went to Australia and played a great part in bringing Australia and Great Britain very close together from the communications point of view.

Dr. Robinson recalled how radio had developed from a scientific experiment, as it was in the early 1900's, to a very potent weapon with powerful potentialities. Under the influence of Sir Ernest, Australian broadcasting policy had adopted the democratic view.

Finally, Dr. Robinson commented upon the importance of the radio institutions in the various countries of the world, whose function it was to take the responsibility of recommending to those in authority the policy which should be followed in respect of radio.

The whole membership of the British Institution of Radio Engineers would wish to join in the expression of thanks to Sir Ernest Fisk, not only for an interesting but a refreshing and thought-provoking address.

The resolution of thanks was put to the meeting by the President, and was carried with acclamation.

Sir Ernest Fisk :

In this review of radio development it is very right to pay tribute, as Mr. McMichael has done, to the pioneering work of amateurs, especially in the short-wave field.

As President of the Wireless Institute of New South Wales, when it was purely an amateur body, I was concerned with the experiment conducted through the company which I represented, for the journey undertaken by a party of amateurs, from Sydney via New Zealand and Fiji, to San Francisco and back in order to extend their experiments. Working on wavelengths from about 80 to 120 metres, they had achieved some excellent results.

Other workers, including Charles Bartholomew and Malcolm Perry, many of whom had carried out outstanding work in the long-distance transmission and reception of short wave signals.

In conclusion, Sir Ernest again expressed his appreciation of the opportunity to address members of the Institution.

The

British Institution of Radio Engineers

PUBLIC ADDRESS SYSTEMS

A discussion by the North-Eastern Section on 29th September, 1943, *and by the Midland Section on 27th October,* 1943. *Opened by :—*

H. Brennan, B.Sc., Grad.I.E.E. (*Associate Member*),
and A. Cross (*Member*).*

Mr. H. Brennan, opening the discussion :—

The art of re-creating or reinforcing sound depends for its degree of perfection, not only upon the correct selection, technical excellence and power reserve of the electro-acoustic equipment employed, but also upon the ingenuity displayed in planning the layout of the installation and operating it to best advantage to suit a given set of auditory conditions.

The primary object of this paper is to promote discussion on various aspects of public address systems, and the author feels that the best way of achieving this purpose is to review present day knowledge of the subject, starting with the elementary principles of electro-acoustics directly relating to difficulties met with in practice, and leading on to suggestions and observations in connection with practical applications of main and auxiliary equipment, according to circumstances.

In the case of indoor public address work, the problems dealt with in this paper concern the effects of reverberation, acoustic shadows, interference, absorption, and ambient noise ; while in the case of outdoor work, all these effects are considered in addition to the effects of echoes, sound drift by wind, and noise from wind.

Past experience gained in overcoming practical difficulties is of great help in formulating requirements for prospective public address installations and therefore brief descriptions and illustrations are given of certain public address work done in recent years. The paper concludes with suggestions for the future development of public address systems. The various aspects dealt with are as follows :—

1. Loudness and the gain control.
2. Reverberation.
3. Interference.
4. Peak power and the amplifier.
5. Microphones.
6. Loud speakers.
7. Layout and operation of complete installations.
8. Description of work done in recent years.
9. Future development of high fidelity systems.
10. Conclusion.

1. Loudness and the Gain Control

Operating the gain control of straight line equipment increases or decreases the amplification of all frequencies in the same proportion, but the human ear does not register these changes according to this linear function,

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* Northern Rediffusion Services, Ltd.

because the sensitivity of the ear to the measurement of loudness varies in a complicated manner with frequency and intensity, and therefore the ear registers unnatural impressions of tone balance, if the level of reproduction is too high or too low, relative to the correct level. The loudness of a tone is not linearly related to its intensity, and the relation between loudness and intensity is a function of frequency.

A decision should be made on what is meant by the "correct level" of loudness; and in the author's opinion, the correct level of sound, music particularly, should be understood as the loudness which a listener appreciates when favourably situated for most pleasantly hearing the original sound. The regulation of the acoustic output, above or below the correct level, is very important in high fidelity reproduction, and should be governed by the extent to which the human ear can register changes in loudness, without, at the same time, receiving the impression of incorrect tone balance.

In high fidelity work, it is generally agreed that tone controls, in the hands of inexperienced operators, are dangerous, but the gain control is also a source of mischief when the operator does not understand the aural interpretation of volume change.

L. C. Pocock (1) draws attention to the distortion due to wrong level of reproduction, and illustrates the point by considering four tones, 100, 250, 1,000 and 4,000 cps, respectively, of equal loudness in the original sound, and which are reproduced with uniform amplification. The original sounds were at 70 dB level, and Pocock shows that reproduction 20 dB too high, raises the virtual frequency characteristic 6 dB at the lower end relative to 1,000 cps, and slightly raises it at the higher end; while reproduction 20 dB too low drops the virtual frequency characteristic at the lower end 12 dB, and slightly lowers it at the higher end.

To illustrate the way in which the ear would measure a change of loudness in an extreme case, the author has produced the graphs shown in Fig. 1.

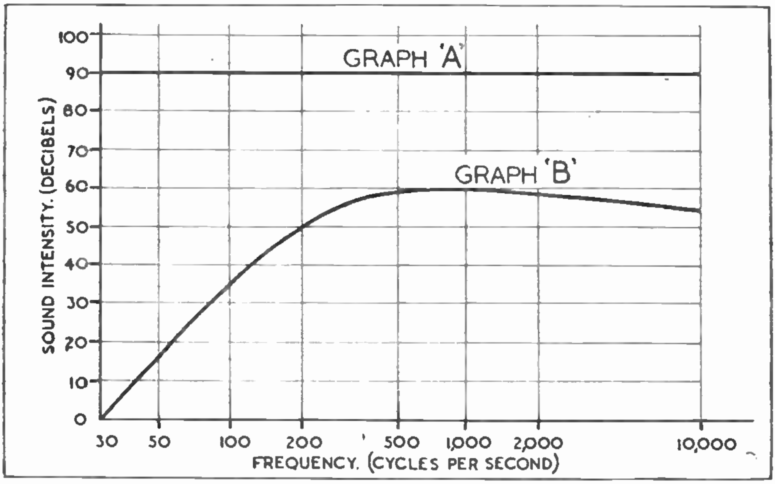

Fig. 1.—Graph " B " indicates the aural impression of the comparative loudness of various frequencies, when the amplification of all frequencies is uniformly reduced from 90 *dB to* 60 *dB, above the threshold of audibility, relative to the* 1,000 *cps note.*

The gain control of a straight line equipment is assumed to have been adjusted to reproduce variable frequencies at 90 dB above the threshold of audibility (referred to 1,000 cps), so that all true tones from 30 to 15,000 cps sound equally loud, as indicated by graph "A." Curve "B" shows the relative loudness of each frequency as judged aurally, when the gain control is turned down until the 1,000 cps note is reduced to 60 dB above the threshold of audibility.

It frequently happens in public address work that sound has to be reproduced at a level far higher than the correct level, and this circumstance is most frequently associated with systems of the concentrated type; the aural impression of such reproduction is one of distortion, the lower frequencies are too predominant, and the intelligibility is poor; a practical remedy is to reduce the amplification of the frequencies below 500 cps, and to a much less extent, attenuate the frequencies above 4,000 cps, but if conditions permit, it is much better to use a well balanced distributive system, and keep the volume as near to the correct level as possible. What has been said in this chapter does not take into account the effects of reverberation, noise, absorption, recording characteristics, etc., each of which must be considered as a separate problem.

2. Reverberation

Reverberation is the resultant effect of a number of reflected images of the initial sound, following each other so rapidly that the ear is unable to appreciate them as separate echoes. The main difficulty in practice is that the build-up in sound due to reverberant disturbance increases with increase of sound intensity, since louder sound takes longer to vanish below the threshold of audibility.

When the sound in an auditorium is evenly distributed, the decay of sound, during a reverberation test, diminishes in a smooth and logarithmic

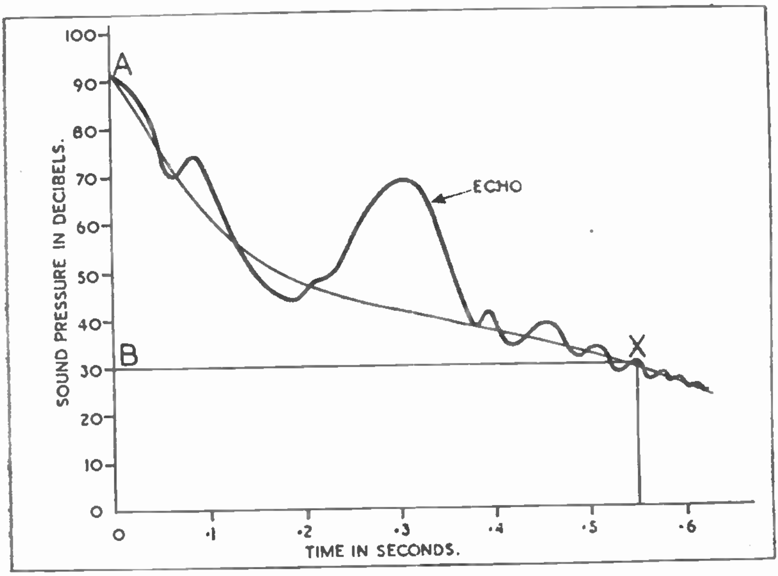

Fig. 2.—Typical curve of decay.

manner, but this favourable condition is very rarely met with in practice, and the usual curve of decay is undulating, as shown by the heavy line in Fig. 2.

If a calibrated microphone with an amplifier and weighting network are available, a C.R. tube in conjunction with precision recorded frequency records may be used to determine the period of reverberation by the method indicated in Fig. 3. The microphone is located anywhere in the auditorium, except within close range of the loud speaker, and the output from the microphone is taken through the voltage amplifier direct to the vertical plates of the C.R. tube.

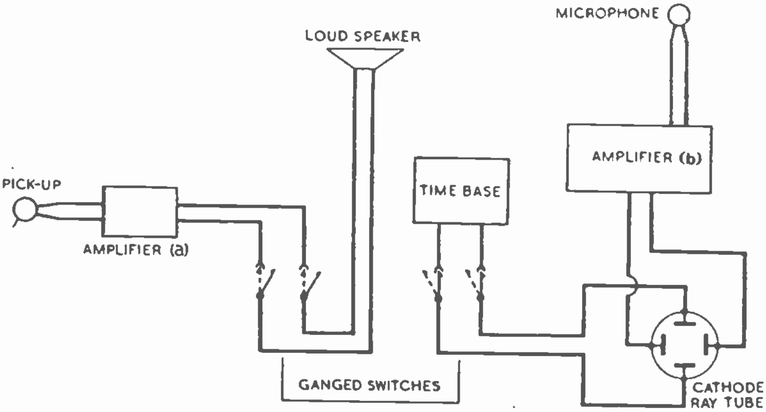

Fig. 3.—Circuit arrangement for determining reverberation period.

The arrangement shown in Fig. 3 is self-explanatory, and for the sake of clarity the key switch is shown as consisting of two double-pole switches, ganged together in such a way that one switch is on, while the other is off, and vice versa.

When the switch levers are in the dotted position, the loud speaker is operated from the pick-up after amplification by amplifier 'a.' On operating the key switch to the right, the switch levers are instantly moved to the positions shown by the full lines, thus the loud speaker is silenced, and the time-base source connected to the horizontal plates of the C.R. tube, so that the oscillograph spot travels at a uniform speed in a horizontal direction. The vertical movement of the oscillograph spot is controlled by the output from the microphone, and the spot will trace out a wavy curve similar to that shown by the thick line in Fig. 2. The vertical deflection of the oscillograph spot is proportional to the sound pressure, providing the response of the microphone is linear. Any large undulations in the wavy curve taking place 0.075 sec. after cut-off, represent outstanding echoes, and the effect of one such echo is indicated in Fig. 2.

The thin line in Fig. 2 is a mean curve drawn through the wavy curve, and this thin curve therefore represents the average decay of the initial sound. The vertical scale of the oscilloscope can be calibrated to read sound pressure in dB, since the intensity of the initial sound can be determined by the calibrated microphone ; thus if a horizontal line BX is drawn at 60 dB below the initial pressure, the period of reverberation is given at the point X, where

BX cuts the thin curve, the time being calculated according to the calibration of the time-base.

In all indoor places of entertainment, mankind is accustomed to hear real music, and speech, in conditions of considerable reverberation, and therefore, if reverberation is removed, something appears to be wrong with the sound ; the sensation of realism is depreciated, particularly if the source of sound is invisible to the audience. A striking illustration of the foregoing effect manifests itself when one compares the sound of a real organ in an acoustically treated auditorium, with that of a similar organ playing in a reverberant church.

The reverberation time is defined as that required for a sound to diminish in intensity by 60 dB, the period being more important with regard to speech than to music, because of the adverse effect of excessive reverberation on the articulation of speech. The optimum period of reverberation is 0.5 sec. for speech and 1 sec. for music.

Optimum reverberation is very desirable, as it not only adds to the sensation of realism, but also increases the intensity of useful sound further, it is well known that the effect of reverberation is to induce an urge for singers and speakers to put forward their best efforts.

Considering a sound source of plus 10 dB (relative to 1 μW), as representing the power of normal conversational speech, the author has produced the curve shown in Fig. 4, showing how the intensity level increases with the period of reverberation in a fairly large auditorium with a space volume of 7,500 cubic metres, the curve being derived from the relation :

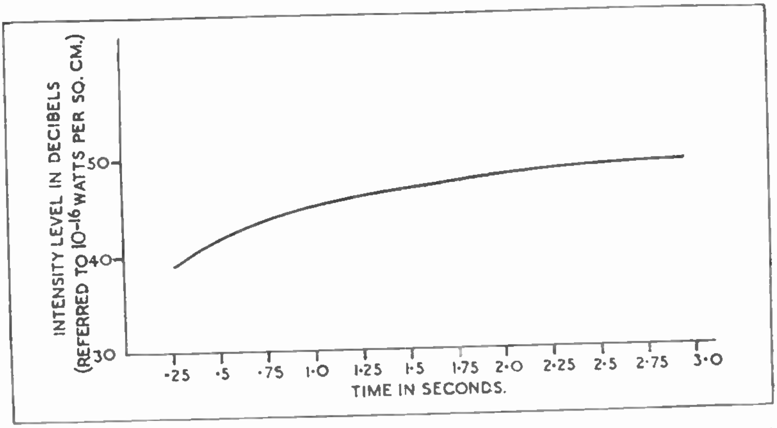

Fig. 4.—Curve showing relation between intensity level and reverberation period.

$L = W - 10 \log V/T + 73.8$, in which

L = the intensity level relative to 10^{-16} watts per sq. cm.

W = the level of the sound source in db. relative to 1 μw.

V = the volume of the auditorium in cubic metres.

T = the time of reverberation in seconds.

A public address system can be adapted to improve intelligibility in a highly reverberant auditorium by using a directional microphone placed as close as possible to the sound source, and in the acoustic shadow of the reinforcing sound, so as to increase to a maximum the pick-up ratio of direct to re-radiated sound and thus keep the " singing " point due to the coupling of direct and re-radiated sound as low as possible. When a concentrated system is used to improve intelligibility, the horn loud speakers should be placed well above seating level, and focussed down on the audience, so that as much as possible of the loud speaker output is absorbed by the audience ; unfortunately, however, and particularly if short horns are used, the focussing of the lower frequencies is not sufficiently directional, and it is necessary to reduce the amplification of the lower register with consequent sacrifice of quality.

In such places as churches, where the reverberation period is abnormally high, intelligibility can be best improved by using a distributive system in which large numbers of loud speakers are directed on to the audience, and operated at relatively low power level, the power being adjusted to mask the effect of reverberation at every point.

Preliminary tests in connection with reverberation usually have to be made in the absence of a full audience, and in one respect this is an advantage, since, if the system can be made satisfactory in an empty auditorium by suitable acoustic treatment, the results will be much better when the auditorium is filled, providing that due allowance is made for the extra power needed to overcome the absorption and noise of the audience.

When auxiliary loud speakers are used for overcoming difficulties due to localised reverberation, acoustic shadows, noise, and interference, the auxiliary loud speakers require to operate at various power levels according to circumstances. and some loud speakers may need to have their bass response severely cut in order to eliminate bass boominess, consequently these loud speakers should be fitted with volume controls which can be operated in conjunction with adjustable tone compensating circuits.

3. Interference

Because of the overlapping of the sound waves radiated by various loud speakers, interference takes place in distributive systems, and in concentrated systems which employ loud speakers in more than one location. Fig. 5 shows what happens in the simplest possible case when there is overlapping

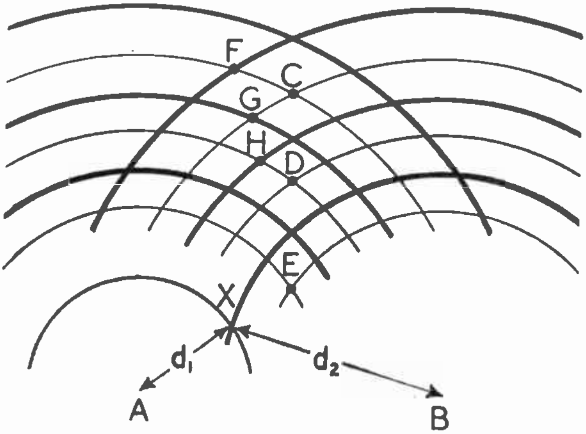

Fig. 5.—Points of interference due to overlapping of the sound waves from two identical sources located at A and B, each radiating the same pure tone, synchronously, and at the same intensity.

of the sound waves from two separate identical sources, each radiating the same single pure tone synchronously, and at the same intensity.

A and B in Fig. 5 are two points at which the air is disturbed synchronously by sources of equal power and frequency. At any particular instant, air rarefactions are indicated by thin lines, and air compressions by thick lines ; thus at points such as C, D, and E, both sources produce rarefactions at the same instant, and half-a-period later these rarefactions become compressions at the same points, and therefore these are points of maximum intensity.

At points F, G and H, a compression wave due to one source reaches the point at the same instant as a rarefaction from the other source, so that these are points of minimum intensity.

Neglecting the effect of reverberation, the intensity at any point X of the sound from A, compares with the intensity at X, of the sound from B, in the ratio $\frac{d_2^2}{d_1^2}$, where
d_1 = distance of X from A.
d_2 = distance of X from B.

It will be noted that X, in the position shown, is a point of minimum intensity, but there will not be total cancellation at this point unless the sources are made to radiate at different levels of intensity in the inverse ratio of $\frac{d_2^2}{d_1^2}$

The neutralizing effect at X is independent of the time difference in sound arriving at X, from A and B respectively, so long as the two sources are radiating the same steady frequency ; thus the conditions at X are identical to the circumstances existing when two similar loud speakers (whose diaphragm movements are in phase) are situated at A and B, respectively and each responding synchronously to only one, and the same, sustained pure tone. It follows that when two adjacent loud speakers are used in practice, both the time difference, and power output of each loud speaker, affect the degree of confusion which occurs in adjacent frequencies at points located according to the overlapping of the polar characteristics of the two loud speakers, and theoretically, at every instant, the air medium must experience the resultant effect of the two sets of sound waves at every point.

From theoretical considerations, interference would appear to preclude the satisfactory use of a distributive public address system ; however, when listening to a weak and strong sound of the same origin, the human ear makes itself unconscious of the existence of the weaker sound, and appreciates only the stronger sound, providing the time difference between the two sets of sound waves is not too long. In practice it has been found that when similar sound is radiated from two sources simultaneously, the time difference between the two sets of sound waves should not exceed 0.06 sec. for satisfactory listening.

Interference due to time difference presents many difficulties in practice, and although these can be overcome in a compromising manner by using auxiliary loud speakers to cover narrow bands of confusion, it is conceivable that in large scale public address systems of the future, the application of time delay will be employed to improve the standard of distribution and fidelity.

4. Peak power and the amplifier

When estimating amplifier input and output requirements, the factor to consider is the value of the peak power involved since this determines the initial grid swing, the capacity of the power valves and the maximum acoustic power which the loud speakers are required to handle without distortion.

For high fidelity work, the amplifier output should be calculated on the assumption that there is total absorption of the loud speaker output when a comfortable listening level is evenly maintained throughout the media of audition ; the extra power required to accommodate the effects of noise and wind must be added to the estimate, and the figure thus obtained again increased to provide the necessary margin for peak power.

If the output of an amplifier is inadequate to accommodate the power peaks when the gain control is set for comfortable listening level, distortion will continue to occur, since manual operation of the gain control is not swift enough to suppress an instantaneous power peak before it causes distortion.

Apart from increasing the power output of the amplifier, the difficulty of accommodating peak power can be overcome in two ways, viz. (1) By reducing the average level of the reproduction, which is obviously unsatisfactory and leads to the form of distortion due to wrong level of reproduction ; (2) by introducing an automatic peak limiting device preceding the amplifier.

The allowance for peak power is dependent upon the ratio of average to peak power, and is greatest when the whole frequency gamut is covered and there is no suppression of the peak passages in the transmission. The full orchestra has a range of 70 dB, and the extent to which this range can be compressed, from the point of view of power economy in large public address installations, is well worthy of consideration.

Owing to the limitations of broadcasting, the range of minimum to maximum power of the original sound has to be greatly reduced before transmission, and in the case of a symphony orchestra the reduction might be from 70 to 40 dB.

The economy in power effected by peak limitation is considerable, thus for example, if the highest range in a broadcast transmission is 40 dB, a further limitation to 30 dB increases the average power of the amplifier ten times.

With regard to the method of limiting peak power, probably the best method is one which leaves the power output exactly as it is up to a certain level, and limits the power to that level ; a system operating on this principle is described by W. N. Weeden. Another method of limiting peak power is

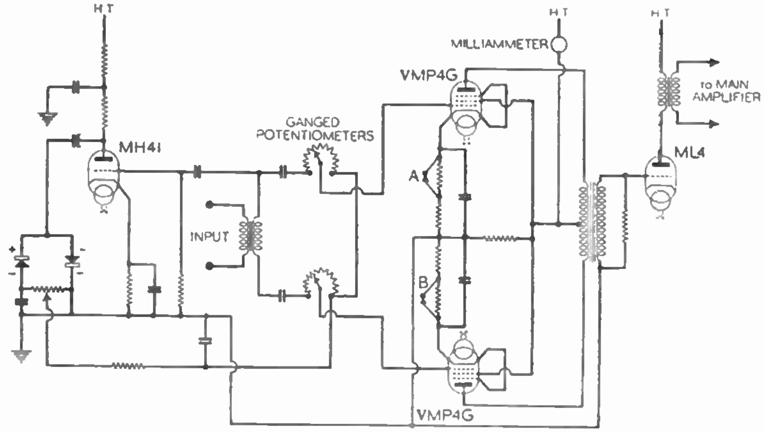

Fig. 6.—Peak limiting device used by the author for insertion in a 600 ohms circuit preceding the main amplifier. L.F. signals fed to the first valve are rectified after amplification by the first valve. The D.C. output of the rectifier automatically regulates the bias of the variable mu valves, thus the amplification is increased as the signal strength decreases.

to contract the range by reducing the loud passages and accentuating the soft passages.

Automatic peak limiting devices have certain practical disadvantages in their application ; S. Hill (3), in his recent paper on Public Address Systems (*J.I.E.E.*, Sept. 1942), points ut the importance of the time interval (in effecting the adjustment) ; if the time is too short, undesirable transients are introduced, and if it is too long, overloading may be apparent during the period of adjustment ; thus, when an increase of input level is followed by a decrease of gain, after a time interval of about 100 milliseconds, the overloading continues for 50 to 250 milliseconds after the fall in input level.

The simple circuit arrangement shown in Fig. 6 has been used by the author to good effect in conjunction with broadcast relay on occasions when it has been necessary to economise in power. The milliammeter shown in the diagram registers the current taken by the two variable mu valves, and, in the author's experimental unit, this meter is calibrated with reference to the effects produced on the wave-form of the transmission in relation to certain settings of the pre-amplifier gain control, and the gain and bias controls of the peak limiting device.

The advantages, and disadvantages, of peak limiting, may be summarised as follows :—

Advantages :—

(1) The economy effected in power output.
(2) The prevention of overload when there are very large variations of input.
(3) Improved regulation of volume.

Disadvantages :—

(1) The peak limiting device requires to be carefully designed and expertly adjusted before being put into commission, and re-adjustment is necessary when the form of transmission changes.
(2) In radio and gramophone transmissions, considerable contraction in the power range has already been done, and in the case of high fidelity reproduction it is questionable whether further contraction is advisable, since too little contrast depreciates the sensation of realism, particularly if the source of the sound is not visible to the listener.

In estimating output requirements, an idea of the peak power in R.M.S. watts radiated by various sources of original sound is of considerable assistance, since, from general experience, one knows approximately how far, and over what area, original sound can be satisfactorily heard ; however, when using such knowledge with a view to assessing how closely output calculations are near the mark, one must bear in mind : (1) the extent to which the peak power of the original sound is reduced, as in the case of broadcast transmissions or gramophone recordings ; (2) the saving of acoustic power which results from focussing loud speakers onto the audience, as compared with the spherical dissipation of acoustic power from the original sound, in which a considerable part is wasted by useless radiation into space. If the equivalent effective electrical power of direct sound can be accurately determined from the foregoing considerations, the power required for reinforcing the direct sound may be closely estimated by referring to an empirical curve such as that due to J. R. Taylor, (4) (*Communications and Broadcast Engineering*, 1937), which shows the relation between output power and size of audience, based on a number of actual installations. The power required for reinforcement may be obtained by deducting the equivalent power of the direct sound from the figure for total power given by the empirical curve, but the result would be subject to modification according to the particular conditions due to reverberation, noise level, wind and peak power.

With regard to the equivalent electrical power of various sources of sound, it is instructive to calculate the quantity in respect of speech. The normal conversational level of speech has been defined as that which produces a reading of 64 dB on a noise level meter at 50″. 64 dB relative to 10^{-16} watts per sq. cm. at 1,000 cps, represents an equivalent electrical power of 2.5×10^{-10} watts per sq. cm., and if this is considered as radiated in every direction from a point source, the total power radiated equals 5×10^{-5} watts.

To arrive at the equivalent electrical power of speech in the most extreme case, allowances in dB above average speech power may be made as follows :—

Plus 9 dB for a speaker who talks above the average. (5), Harvey Fletcher in his well-known book, " Speech and Hearing," shows that 4 per cent. of speakers talk as much as 6 to 9 dB above the average.

Plus 5 dB for increase in voice level due to the speaker being immersed in very considerable noise due to heavy wind and traffic, say a noise level of 80 dB relative to 10^{-16} watts per sq. cm., L. C. Pocock(1).

Plus 12 dB for maximum peak power above average level, (6), (L. J. Sivian, " Speech Power and its Measurement." *Bell System Technical Journal*, Vol. 8, p. 646).

The above considerations show that the peak power of speech in extreme conditions may be as high as 2×10^{-2} watts, or plus 13 dB relative to 1 mW.

There are several ways of estimating the power required by loud speakers on a basis of room size, and an illustration may be given by calculating the output required for normal conversation in an average living room, using the method due to G. E. Morrison (7).

Morrison calculates the area over which the sound flows by direct radiation of the loud speaker, and multiplies this area by the watts per sq. cm. corresponding to the level required. The effect of reverberation in the room is considered to be negligible.

The area " A " over which sound flows by direct radiation is given by the expression : $A = 2\pi \, (OP)^2 \left(1 - \cos \frac{\theta}{2}\right)$,

where OP = half the length of the room,

θ = angle of planar radiation of the loud speaker, being determined at 500 cps for speech. [In example, $\theta = 114°$]

The area " A " for a room 16′ long, when using an average domestic loud speaker works out at 1.7×10^5 sq. cm., and taking a level of 64 dB relative to 10^{-16} watts per sq. cm. the acoustic power required is approximately 4.25×10^{-5} watts, thus if the efficiency of the loud speaker is 5 per cent., the amplifier power required is 8.5×10^{-4} watts, or plus 29.3 dB with respect to 1 μW., but the figure must be increased according to the factors already discussed.

5. Microphones

Apart from the standard of fidelity required, the choice of a suitable public address microphone depends entirely upon the nature of the sound to be transduced and the local conditions. For example, when highly directional response is necessary, the best type of microphone to use is one which operates as a pressure device (depending for its operation on the action of sound pressure on one side only of the diaphragm), and can be fitted with a system of tubes (8), S. Hill, *J.I.E.E.*, Fig. 6, p. 127, which have the effect of cancelling out sound waves approaching from the sides, but not from the front, of the microphone ; on the other hand, such a device is not satisfactory when wind is present, since the passage of air across the openings of the tubes transmits noise into the microphone.

Generally speaking, the requirements for a public address microphone are :—

(1) Good linear response.
(2) Robustness.
(3) Freedom from self-generated noise.
(4) Directional polar characteristic.
(5) Moderately low impedance.
(6) Reasonably high sensitivity.
(7) Good shielding from the effects of wind.

A well designed moving coil microphone complies with the above requirements, and probably this is the reason of its present popularity in most forms of public address work. The advantages and disadvantages of various types of microphones are given briefly, as follows :—

Carbon Microphone.

Advantages :—

High output resulting in economy of amplification, and in certain cases making it possible to dispense with the use of a pre-amplifier.

Disadvantages :—

(1) Non-linearity of response caused by reflections from the back of the granule chamber, and selective response of the granules ; the non-linear effect being most noticeable at frequencies where the amplitudes are greatest.
(2) The output falls rapidly as the sound intensity diminishes.
(3) A battery is required to provide energising current.
(4) Self-generated noise is introduced to the microphone output.

Crystal-diaphragm microphone.

Advantages :—

(1) Freedom from self-generated noise.
(2) In certain circumstances the output may be connected directly to the pre-amplifier without the use of transformers.

Disadvantages :—

(1) Response not strictly linear.
(2) High impedance, approximately 80,000 ohms at 60 cps, calls for very high value of grid input resistance.
(3) Pre-amplifier input circuit requires careful screening, and calls for low " hum " level.
(4) Advantage of direct coupling to pre-amplifier only available when distance between microphone and pre-amplifier is short, as there is a loss of L.F. response due to capacity of transmission cable.

Condenser microphone.

Advantages :—

(1) Good linear response.
(2) Freedom from self-generated noise.

Disadvantages :—

(1) The microphone is not robust.

(2) High impedance results in disadvantages similar to those of crystal-diaphragm microphone.

Moving conductor microphones.

The advantages of the moving coil type have already been given; the disadvantages are :—

(1) If there is asymmetry of the coil relative to the magnetic field, harmonics as much as 10 dB below the fundamental are produced, even if the coil movement is very small.

(2) When the microphone does not operate as a pressure device, the response alters when the sound source is at different distances from the microphone.

Ribbon microphone.

The advantages and disadvantages of a ribbon microphone are similar to those of a good moving coil microphone, except that the sensitivity is usually lower. The ribbon microphone is a pressure gradient device which depends for its operation on the resultant of sound pressures acting on both sides of the diaphragm, which is sufficiently small to offer negligible obstruction to the passage of a sound wave.

Cardioid microphone.

By incorporating a pressure operated coil element in the same case as a ribbon element, and combining the respective outputs in varying proportions, a large number of polar characteristics may be obtained, and the combined instrument is called a cardioid microphone. The cardioid microphone may thus be made very useful for special purposes, owing to its possibilities for responding to random sound ; on the other hand, constructing the dual microphone for this purpose, reduces the robustness and allows less freedom from wind noise.

Crystal sound cell microphone.

The author has had some experience with this type of microphone in connection with public address systems in theatres.

In the standard crystal sound cell microphone, the crystal units are approximately 7/16 sq. inch, and from 0.02 to 0.03 inch thick ; the two sections forming a Bimorph unit, without their electrodes, being approximately 0.006 inch thick. The crystal units are designed to resonate at 12,000 cps, causing the response characteristic to rise at the upper end.

The impedance of a single sound cell is equivalent to a capacity of .0033 μF, or 1,000 ohms at 1,000 cps. Any number of cells may be incorporated in a microphone according to the output required, and as the cells are series-paralleled, the capacity of any assembly is never less than that of a single cell.

Apart from the operational disadvantages of high impedance, which necessitates an input grid resistance of not less than 5 megohms, the advantages are numerous ; it is robust and unaffected by mechanical shock. There is very little distortion of wave front, since the sound cells are arranged edgewise to form a grille, which also reduces reflection, pressure doubling, and cavity resonance ; no energising current is required, and there is freedom from background noise.

Since the sound cells are themselves capacitative, the capacity of the microphone leads has no effect on the level of the response characteristic ;

the effect of shunting capacity is only to lower the output, the reduction affecting every frequency equally.

One type of sound cell microphone is specially designed to operate on the floor of a stage, and this model has eight sound cells arranged in four groups of two in series, connected in parallel. Very good results can be obtained by using two of these microphones in series, and more than one such pair can be used to give added effect, if the output from each pair is taken to a separate pre-amplifier.

A successful system used by the author employed two "stage" type crystal sound cell microphones connected in series, spaced 10 feet apart on the stage floor, approximately 18 inches from the front edge of the stage.

There is a laboratory crystal sound cell microphone available in which the input to the pre-amplifier is accurate to 0.5 dB from 30 to 15,000 cps. In the laboratory instrument, the sound cells are one quarter the area of those used in the standard models, and they have a calculated natural frequency period of 36,000 cps. The cells are mounted in a spherical wire cage, 1½ inches in diameter, supported at the end of a short tube which serves to screen the grid lead, and prevents interaction from the pre-amplifier, which is enclosed in a screened case at the foot of the tube.

6. Loud Speakers

Great advancement has been made in perfecting the performance of loud speaker driving units, and although in this respect a high standard of performance has been obtained, there still remain rather compromising methods of coupling a single driving unit to the surrounding air, in so far as the low frequency response is concerned. The construction of driving units to give even response down to 30 cps without resonance is possible, but it is not a simple matter to devise means of utilising this low frequency response, without the use of the tremendous size of baffle, or horn, required for adequate air loading.

A baffle increases the length of the air path from the rear to the front of the diaphragm, thus preventing cancellation of the low frequencies, but since the wave-length of a 30 cps note is approx. 37′, it is impossible to accommodate the necessary size of baffle in practice, and other means of obtaining the bass response have to be employed.

In the case of domestic loud speakers of the cabinet type, the loss of bass response is usually overcome to a great extent by arranging the stiffness of the suspension of the diaphragm, so as to produce resonance at a low frequency, but unfortunately, this introduces small resonances at higher frequencies, as well as causing frequency doubling below the fundamental frequency.

There is a form of domestic loud speaker in which the radiation from the reverse side of the diaphragm is confined within a sealed box for the purpose of producing a resonator effect, whereby the sound output is considerably augmented at the resonant frequency of the system. The success of the resonator calls for a loud speaker unit in which there is practically no mechanical restriction of diaphragm movement, so that the frequency of fundamental resonance is extremely low. The stiffness of the cone suspension increases due to the stiffness of the air inside the sealed box, the result being that there is a rise in the resonant frequency when the unit operates in the box; thus, if the fundamental resonance frequency of the unit is 50 cps in free air, it may be well over 100 cps when the unit is mounted in the cabinet. The conclusion is that a resonator cabinet system is not satisfactory, unless the fundamental resonance frequency of the loud speaker unit is of such very low order that an ultimate resonance below 50 cps is obtained when the unit is mounted in the cabinet.

The air loading of horn loud speakers depends upon the length of the horn, and the size of the flare, and theoretically, the diameter of the flare should be one quarter the wave-length of the lowest frequency to be reproduced. The shape of a horn is important, and it is essential that the axis should be straight. As pointed out by P. G. A. H. Voight (9), the wave front must join the horn surface at right angles, and this determines a horn shape following a Tractrix curve, the law for which is that the length of the tangent to the centre line is constant. In arriving at the exponential horn design, it is assumed that the wave front is flat, and although this is of negligible account at the throat end of the horn, it introduces considerable errors in the horn mouth.

The attenuation of the lower frequencies in short horns precludes them from being classed as high fidelity reproducers, but this does not make the reproduction of concentrated systems unacceptable, since the usual function of short horns is to provide intelligibility, and a lack of bass response can be tolerated in such circumstances, particularly if the source of the direct sound can be seen by the audience.

Much scientific development has taken place with regard to the design, and methods of air loading, of electro-dynamic driving units for horn loud speakers. In the original electro-dynamic unit, radiation from the front, only, of a domed diaphragm was used, and in order that each sound particle leaving the diaphragm should reach the throat of the horn without random phase cancellation, it was necessary to construct a narrow passage between the diaphragm and the throat, the dimensions of the passage being such that each sound particle travelled the same distance before arriving at the throat, and to achieve the purpose, a centre-piece, resembling a sharp pointed pear, with the point directed towards the diaphragm, was suspended rigidly inside the enclosure between the diaphragm and the throat.

The latest type of electro-dynamic unit makes use of radiation from the rear of the diaphragm, the radiation being passed to the horn through narrow passages in the central pole, the idea again being to reduce random phase cancellation and strengthen the output at high frequencies.

It is worth mentioning that horn loud speakers with electro-dynamic units have been developed down to very small sizes, measuring as little as 8 ins. in diameter and 2 ins. from back to front ; the efficiency being about 20 per cent, and the low frequency cut-off 800 cps. A loud speaker of such small dimensions can be very easily camouflaged, and there it is very useful for focussing high frequency over an acoustic shadow, or narrow band of confusion, without drawing the attention which a standard type of loud speaker would do.

7. Layout and operation of complete installations

The arrangement and type of auxiliary equipment employed between the microphone and the main amplifiers must necessarily vary according to circumstances. Pre-amplifiers are generally located as close as possible to the microphones, this condition being essential when the mixing of the outputs of a number of microphones is required, and when the pre-amplifier incorporates the main gain and tone controls of the system.

Except in the case of diffusion systems, there is very little standardisation with regard to the layout of the equipment and the arrangements of connecting loud speakers to the output transformer ; and, for accurately matching the output load, many systems rely upon various combinations of series-paralleled loud speakers operating in conjunction with an output transformer, which has a multi-tapped secondary winding.

Apart from non-standardisation, the disadvantages of series-parallel connection of loud speakers may be summarised as follows: (1) The performance of the output transformer is adversely affected by a multi-tapped secondary winding, since, even if the transformer can be designed so that there is a symmetrical arrangement of the secondary winding for every tapping provided, there is always idle copper in the secondary winding when it is not fully in use. (2) When there are long series and parallel line interconnections among a large number of loud speakers, there is a complication in assessing the effect of the capacitance and inductance of the output lines.

From a practical point of view, the best output arrangements exist when all the loud speakers are connected in parallel and a constant voltage is maintained across the lines.

Amplifiers employing a class A-B output stage (which may use high efficiency beam power pentodes operating with negative feed-back), operate at almost constant output voltage between the limits of open-circuit and optimum load conditions, and therefore there is no distortion in the output circuit when the working load impedance varies, providing the working load impedance is always greater than the impedance of the output stage.

Public address installations in hospitals, schools, factories, etc., are examples of cases where the working load impedance is continually varying, since it is necessary to control the volume of individual loud speakers and switch loud speakers in and out of circuit, without altering the ratio of the output transformer; the loud speakers in such installations are best operated from a class A-B output stage, for the reasons already explained.

When discussing the operational aspects of public address equipment, mention should be made of the methods employed for controlling the volume of individual loud speakers, since this problem presents peculiar difficulty, and one still finds two methods used in practice, each of which is more or less unsatisfactory, viz.: (1) Adjusting the volume by connecting the loud speaker speech coil to various tappings on the secondary of the speech coil transformer, which results in mismatching, and produces frequency distortion. (2) Adjusting the volume by means of a potentiometer or series resistance,

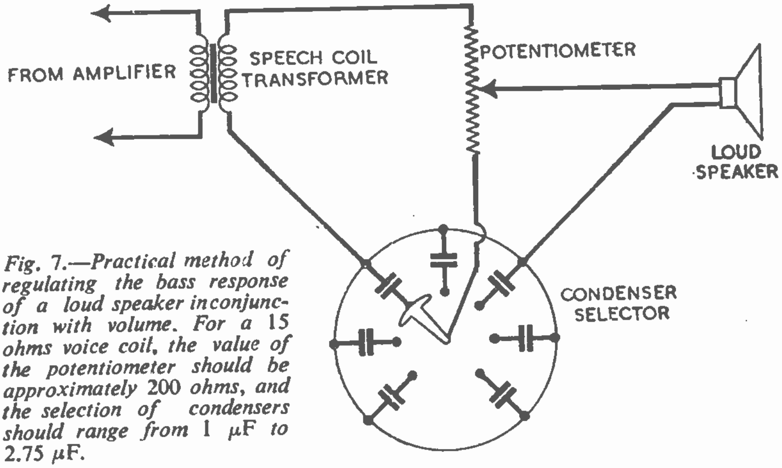

Fig. 7.—Practical method of regulating the bass response of a loud speaker in conjunction with volume. For a 15 ohms voice coil, the value of the potentiometer should be approximately 200 ohms, and the selection of condensers should range from 1 μF to 2.75 μF.

which not only absorbs useful power, but also causes a loss of bass response due to the impedance of the loud speaker being much greater for high, than for low frequencies.

Possibly the best method of controlling the volume of individual loud speakers is to use the arrangement shown in Fig. 7, in which several condensers of various capacities can be selectively put in series with a potentiometer, thereby providing means for regulating the bass response according to requirements.

There is not space in this paper to describe and illustrate the layout and operation of a number of different public address installations, but in order to stimulate discussion on the subject, consideration will be given to the case of a fairly large installation in which two different schemes for achieving the same object are compared. The installation under review may be considered as one required for providing public address over a large area to many departments of a large factory, or for providing extensive entertainment in the open, where in both cases a total power output of 0.25 kW is required.

Fig. 8 illustrates a possible layout when one amplifier is employed to provide power to five groups of loud speakers, and Fig. 9 illustrates an alternative layout when each group of loud speakers is fed by a separate amplifier. In the first scheme shown in Fig. 8, all the power of the single amplifier may be transmitted to the distant points at high voltage, say, 200 volts (R.M.S.), suitable step-down transformers being used at the distant points for distributing the power to the various groups of loud speakers. If the route length of each of the five feeders is 1,000 yards, and No. 16 S.W.G. line wire is used, the line loss at full load under balanced conditions is approximately 4½ watts.

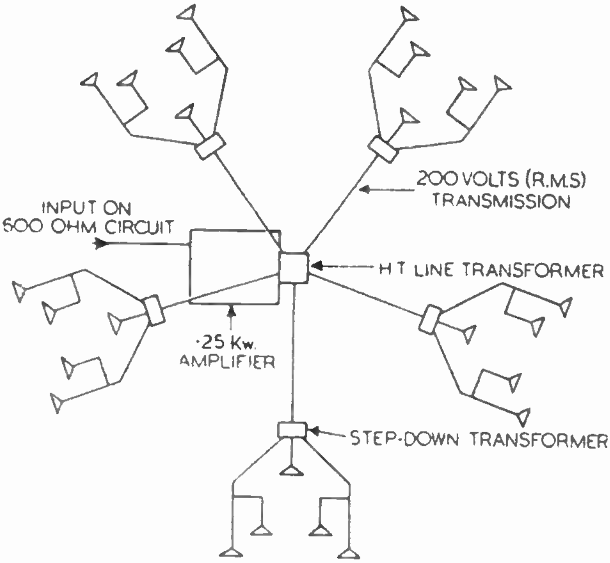

Fig. 8.—Distribution of power from central control point by transmission lines operating at 200 volts, R.M.S.

The use of large line transformers increases the risk of load mismatching and adds to the loss in the transmission, and another point of some importance is that the control of the system is not sufficiently flexible.

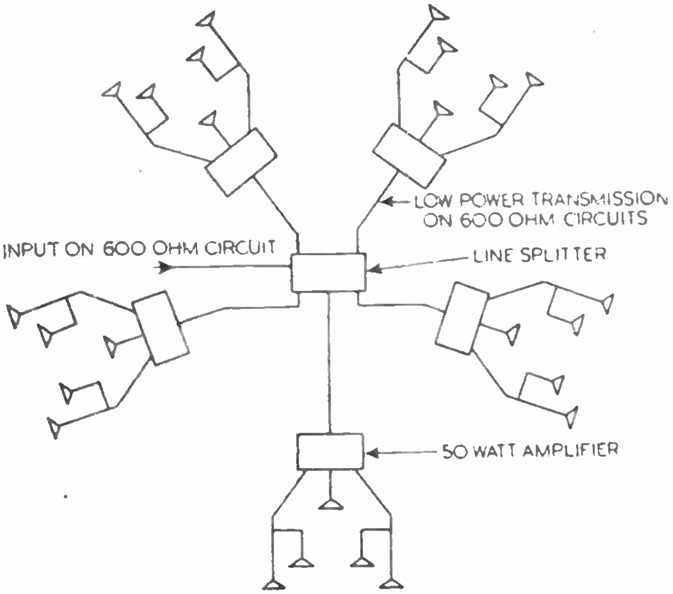

Fig. 9.—*Transmission of signals from central control point to remote amplifiers, using low power* (1·5 *to* 2 *volts peak*), *on* 600 *ohm circuits.*

In the second scheme, Fig. 9, a line splitter is used in order to provide five outlets from the single output of the pre-amplifier, so that signals at low power (1.5 to 2 volts peak) may be conveyed to the distant amplifiers via standard 600 ohm line circuits, a method which results in negligible loss of power or quality in the transmission. The control of this system is much more flexible than that of the first scheme, since the output of each group of loud speakers may be regulated by the gain and tone controls of the amplifier on the spot, and, if noise conditions vary only from group to group of loud speakers (not from loud speaker to loud speaker), adjustments to meet the particular requirements at each location can be made very quickly.

For the particular circumstances described, low power transmission is preferable to high power transmission ; but the circumstances are frequently such that the reverse is the case ; thus in the instance of diffusion systems the first scheme is ideal, and the second scheme would only be adopted when very long distances between amplifying stations are involved.

The layout and operation of a public address system must take into account the effects of wind and noise, since these factors restrict the attainment of high fidelity reproduction and call for increased input and output signals.

Noise which originates in the electro-acoustic equipment due to valve hiss, microphone hiss and mains hum, may be eliminated to negligible proportions by careful design, and for high fidelity reproduction the level of such noise should not be less than 50 dB below the input signal level or more than 3 dB above thermal agitation (⁸).

Noise which is independent of the electro-acoustic equipment, such as noise caused by the audience, or by traffic, or wind, necessitates a high level of signal input, a satisfactory input level being 30 dB above basic noise level.

Wind at the microphone may cause the moving element to flutter, and at the same time create noise in passing across the exterior edges of the microphone case ; both effects depend upon the construction of the microphone, and may be partially eliminated by fitting the microphone with a suitably designed wind screen.

Wind blowing against the sound radiated by a loud speaker weakens the sound intensity, particularly near the ground level, and since wind moves at a greater speed higher up than nearer the ground level, the sound waves are refracted in an upward direction.

Compensation for the effect of wind at the output end of the system involves giving the loud speakers more power and tilting them more towards ground level, than would be the case in conditions of calm weather.

In the case of speech, the successful operation of a well laid out installation depends in no small degree upon the way in which the speaker talks and behaves in front of the microphone. If the speaker moves about in front of the microphone, one solution of the difficulty is to use more than one microphone in the vicinity of the speaker, and an alternative is to equip the speaker with a lapel microphone ; in the former case the microphones would be placed according to their polar characteristics, so that the speech would always come well within the range of at least one microphone, and in an event of sufficient importance, automatic regulation of the resultant output of the several microphones may be justified.

8. Description of work done in recent years

(*a*) *Public Address System at the Thirty-First International Eucharistic Congress in Dublin*, 1932.

Over one million persons were catered for by this large scale public address undertaking, which involved, among numerous other functions, the feeding of over 400 loud speakers spread over a route length of 15 miles, in addition to feeding 34 loud speakers, covering a congregational area measuring one mile by one half-mile. There is not space in this paper even briefly to describe the layout, but a general idea of the magnitude of the system and the distributing arrangements may be gathered from certain photographs which, by the kindness of Messrs. Standard Telephones & Cables, Ltd., the author was permitted to show during the reading of this paper.

(*b*) *Public Address System at the Bede Centenary Celebrations, Jarrow-on-Tyne.*

The public address requirements for the Bede Centenary Celebrations, which were executed by the author in 1933, involved reinforcing sound in the open air and distributing it over an area occupied by some 70,000 persons who were facing an altar erected midway on the long boundary line of a large rectangular playground.

The ground in front of the altar had an even and rather gentle rise, so that acoustic conditions were ideal, except for strong echo from a single large building situated in an adjoining field behind the audience and directly opposite the altar.

Preliminary tests were made to determine the best arrangement for distributing the sound and eliminating the echo, and the most suitable layout consistent with the equipment available was finally found.

Two large horn loud speakers were mounted on 8 foot pylons at points A and B, these being points at which direct sound from the altar was just commencing to be unsatisfactory. The horns were given a downward tilt on to the audience, the optimum angle being determined by trial and error, and in this way the audience at each end of the playground was well catered for. An important feature of this arrangement was that the loud speakers were pointing in almost opposite directions, and therefore the sound from the loud speaker at A was almost inaudible to the section of the audience within the focus of the loud speaker at B, and likewise the sound from the loud speaker at B was almost inaudible to the section of the audience within the focus of the loud speaker at A.

In order to overcome the echo from the large house, and at the same time distribute sound evenly over the central part of the congregation, it was decided to use at point C, a 360 deg. radiator of the inverted type, as illustrated in the photograph. The distance from point C to point A was 65 feet, and as this was equal to the distance from C to B, the time difference of sound waves heard simultaneously from C and A, or from C and B, did not exceed .06 sec., and consequently the effect of interference was negligible.

Two crystal-diaphragm microphones were used on the altar for the delivery of the religious service. Each microphone was coupled by a short transmission cable to a separate battery-operated pre-amplifier, the outputs of the pre-amplifiers being mixed, and the resultant signal split into two circuits, one of which was connected to a 12 watt amplifier feeding the 360 deg. radiator, and the other connected to a 24 watt amplifier feeding the two horn loud speakers.

The amplifying equipment was housed under the altar platform, and the control of the system from this point was carried out satisfactorily by aid of monitor headphones.

(c) *Public Address System at a London Dirt Track.*

By the kindness of Mr. P. G. A. H. Voight, the author has been permitted to describe a system designed by Mr. Voight for use on a London Dirt Track, just prior to the outbreak of the present war.

It will be realised that the satisfactory distribution of sound for some 50,000 persons on a dirt track is rather an exceptional problem, when one considers the variations in noise levels due to a number of motor cycles continually tuning up their engines.

Experiments have been made by using a number of horns, but walking round such a concentrated system gives a continuous change in the sound quality as one gets on to, and departs from, the projecting line of the several loud speakers.

With an arrangement using radial reflection from the centre of the course, the sound quality is substantially uniform all the way round the course.

The central sound distribution system utilizes four highly efficient double-diaphragm moving coil units facing downwards on to four throats which branch into a Treactrix horn with a 4-foot flare, the latter pointing on to a 360 deg. reflecting surface, which distributes the sound evenly in all directions.

There was a difficulty due to the track being oval, which made additional power necessary in the direction of the long axis ; and it was necessary to employ two additional horn loud speakers situated part way down the field. No difficulty was experienced due to time difference (probably about 0.1 sec.), and the persons operating the system were satisfied that they had better public address quality than that on any other track in the London area.

The sentry box was not used by the commentator but was occupied by one of the officials who had something to do with the racing ; his complaint was that the vibration tickled his feet, but a few thick doormats provided the solution.

The microphone, together with twin turntables, and other equipment were housed in a building at the side of the track.

9. Future development of high fidelity systems.

Future planning of permanent public address installations should envisage the highest possible standard of perfection, and for open air schemes this demands that the site for audition should be contoured to provide optimum acoustic conditions. It follows therefore, that if the scientific development of high fidelity sound distribution is to find a foremost place in post war planning, architects and surveyors, responsible for the design of both indoor and outdoor places of entertainment, must work in conjunction with engineers trained in the technique of high fidelity reproduction.

Apart from the essentiality of perfect acoustic conditions, high fidelity reproduction demands freedom from all forms of distortion which may originate in the electro-acoustic equipment, and in this respect scientific development may be said to have reached a high standard of perfection, the degree of which, in commercial applications, is limited mainly by the cost of the apparatus used.

Considerable advances have been made in improving the performance of microphones and loud speakers, but there is still room for more research in connection with improving the linear relation between diaphragm deflection and load, at large amplitudes.

The effect of transient distortion due to non-linear elements does not appear to have been fully investigated, and future research may lead to yet greater perfection in high fidelity reproduction, since the more faithfully the high frequency register is reproduced, the less should be the transient distortion.

In large scale high fidelity public address systems there is great scope for the future scientific development of auditory perspective in the reproduction, and the use of time delay at all points where such reproduction is reinforced.

The perfection of the sensation of realism is the attainment to be aimed at, and this not only calls for sound to be reproduced in perspective detail, but also demands that the sound should be radiated from a central zone of appreciable dimensions, rather than from a point source ; thus probably the nearest approach to ideal radiation is provided by using a large 360 deg. reflecting surface, similar to the arrangement designed by Mr. Voigt for the London Dirt Track, previously described in this paper.

A theoretical requirement which applies in every instance of reinforcing high fidelity reproduction, is that the additional sound introduced should be delayed by the time interval taken for the distant sound to reach the location of reinforcement. On both theoretical and practical grounds, a system employing time delay is a step forward in attaining perfection of sound distribution, but in practice, except with gramophone records, the difficulty is in obtaining the desired effect.

In the case of gramophone reproduction, time delay may be obtained by the use of several pick-ups stationed round the circumference of the turntable and spaced at the required distances apart, care being taken that the pick-ups are all playing in the correct groove. Special gramophone equipment is of course needed for permanent installations.

For the reproduction of direct speech or music, the author suggests that transmissions may be time delayed by means of steel tape machines, in which the tape is used as a loop, so that it can run round and round indefinitely, being wiped at each revolution. Steel tape in the form of a loop would provide no waste, and the speed of the tape could be adjusted so as to give optimum results from a quality point of view. It would be interesting, and probably worth while, to investigate the practical possibilities of this principle.

10. Conclusion

The general conclusions are that it is best to estimate the requirements for prospective public address installations by reference to previous work done, and to arrive at the optimum layout by the trial and error method, used in conjunction with technical knowledge and past experience.

Standardization of complete sound amplifying installations has been prevented in past years due to the widely divergent applications of public address systems, but a brighter outlook for standardization of future permanent installations is conceivable, if scientific development in building and town planning raises the standard of acoustic conditions to some definite level in all places of entertainment. On the other hand, the increasing use of large and small scale systems, catering for passing events in everyday public life, must continue to be done by a great variety of different methods, dictated by individual ingenuity in overcoming the problems presented by each particular case.

The author desires to convey his thanks to Messrs. Standard Telephones & Cables, Ltd., and Mr. P. G. A. H. Voigt for kindly permitting him to describe their systems in this paper, and to show the photographs relating thereto, during the reading of the paper.

Mr. A. Cross

Audio-frequency engineering now has a wide application, and it is therefore surprising that so much of the sound reproduction heard in public places is of such a poor standard. Distortion, lack of volume, bad articulation, over-emphasis of sibilants, hum, crackling and feed-back, are some of the faults that beset many of the public address installations in the provinces —particularly those set up temporarily at public meetings, pageants, and the like ; even specially designed loudspeaker vans, such as those used by the Ministry of Information, give a quality of reproduction which leaves much to be desired.

The basic cause of these troubles are due in most cases to four main reasons :—

1. Insufficient overall gain in the amplifying equipment.
2. Inadequate power for the area to be served.
3. Careless, or uninformed, installation.
4. Bad operation.

The first two points enumerated are concerned with the design of the apparatus and the size of the installation, having regard to the area to be served, as well as the purpose for which the installation is required. Judging from results many public address engineers fail entirely to discriminate between the two contrasting requirements of sound reinforcement—used in theatres to supplement the voice of a speaker or a singer—and sound diffusion —or public address proper—in which a speech may be amplified to a large body of people, some of whom may actually be out of sight of the speaker.

Dealing first with the question of overall gain: in order to estimate the gain required it is necessary to have an accurate knowledge of the characteristics of the microphone, and this is not quite such a simple matter as it should be, for some manaufacturers are inclined to be lax in their microphone specifications. In consequence, we get a curve issued by the manufacturer which tells us that at some selected frequency a microphone gives an output of – 50 dB, but we are not told the reference level.

If the output of a microphone is going to be expressed in this particular way, the reference level must be stated, and also the load resistance across which the microphone was generating voltage when the measurement was taken. Microphones are sometimes rated in terms of decibels below 1 volt ; in other cases they may be rated in decibels below zero level of 6 milliwatts ; again, a zero level of 1 milliwatt is used very widely. Other reference levels used by microphone manufacturers are 10 milliwatts, and 12·5 milliwatts, the latter being used by R.C.A.

A common rating appears to be in decibels of voltage relative to a basis of 0 dB equals 1 volt, for a sound wave having a pressure of 1 dyne per square centimetre. Again, microphones are sometimes rated in volume units (V.U.) ; the output level in V.U. is numerically equal to the number of decibels above or below a standard reference level of 1 milliwatt in 600 ohms.

This indicates that some standardisation of microphone ratings is desirable, and it is obviously necessary to be very careful to ensure that the reference level of the particular microphone being used is understood before any attempt is made to calculate the overall gain necessary to follow such a microphone for a particular installation.

The moving coil and ribbon types of microphone have achieved wide popularity in connection with P.A. work, and the former is the most widely used.

Carbon microphones, even those which are highly damped and have a relatively low output, have been abandoned, due to the fact that they give an unsatisfactory signal to noise ratio in sound reinforcement systems where the overall gain is likely to be of the order of 100 decibels. Under such conditions thermal agitation in the conductors of the input circuit is a factor to be reckoned with in establishing signal to noise ratio, and a microphone giving the best possible signal to noise ratio must be used.

There are practical difficulties attendant upon the use of condenser and piezo electric types of microphone, due to the necessity for soundhead amplification, and this is why the electro-magnetic types are now in general use.

Notwithstanding the higher output and greater popularity of the moving coil instrument, I personally favour the ribbon type of instrument, whilst recognising that the moving coil microphone is more robust and that it has much greater freedom from wind noise. Nevertheless, the velocity ribbon type has compensating advantages.

Ribbon microphones are either pressure operated or velocity types. The pressure operated type has one side of the ribbon freely accessible to the atmosphere and the other side terminated in an acoustic impedance. This type has not the advantages of the velocity microphone, in which the electrical pressure corresponds to the particle velocity resulting from the propagation of a sound wave through an acoustic medium.

One of the important advantages of this type of microphone, compared with the pressure operated type, is that it possesses marked directional properties. It also has a uniform output over a wide frequency range.

The natural frequency of the ribbon is below the audio frequency range. In a condenser microphone, on the other hand, two resonances occur within the audio range that have an influence on the output ; cavity resonance and diaphragm resonance.

The velocity ribbon microphone has a figure-of-eight directional response, and the voltage output of such a microphone for sounds originating in random directions is :—

$$Ev = Eo \cos \theta$$

The voltage output for a non-directional microphone for sound originating in any direction is :—

$$Ev = Eo$$

If we assume that both microphones have the same sensitivity for $\theta = O$ it can be shown that the efficiency of energy response of the velocity ribbon microphone, as compared with the non-directional microphone for sounds originating in random directions, is only one-third.

The advantage of a characteristic such as this, for cutting down feedback and background noise in public address installations and for balancing orchestras and arranging actors, will be readily appreciated.

With regard to the problem of wind noise when using this type of microphone for open-air functions, this can be greatly reduced by the use of a fine silk screen, mounted on a spherical wire framework, so as to enclose the microphone entirely. Acoustic damping of speech is negligible with this arrangement, but wind noise is much reduced.

In a typical sound reinforcement system, the voltage output may be of the order of 100 volts for an input of 1×10^{-3} volts, representing a gain of 100,000 times. Under these circumstances, the input circuits of the speech input equipment need to be most carefully screened, and microphone lines must be kept at a low impedance level, so as to avoid any risk of unbalance giving rise to hum or other induced noise.

Mixers for providing combined input from a number of microphones need to be carefully designed, so as to be free from noise and stray pick up, and in this connection it is useful to note that the mixing of microphones is best carried out at some intermediate point in the chain where the signal level is higher. The impedance level at which mixing is best carried out is of the order of 600 Ω, and this can easily be arranged in cases where each microphone has sound head amplification.

Moving coil microphones having relatively high output at an impedance level of some 200 Ω, can be mixed directly in a most satisfactory manner.

The design of mixing circuits is too varied and complex a subject to go into in this discussion, but it may be said that as a general rule it is desirable that the input voltages to all channels be as nearly equal as possible, so that similar settings of the controls will produce similar output voltages. This means that in cases where it is necessary to mix pick up and microphone output, the latter should be raised in level by a single stage of amplification, prior to mixing.

Consideration of mixers and mixing arrangements leads naturally to a consideration of methods of control. It is absolutely essential that there should be a control and switching panel for every public address job, both large and small ; moreover, an operator of some skill needs to be in constant attendance if the best results are to be obtained.

The technique for the manipulation of a public address system to give the best result is somewhere between that of an outside broadcast and a studio performance. The control operator is required to exercise some skill in the correct placing and mixing of his microphones, and cross fading with incidental music or special sound effects provided by disc. To do this, he must be so positioned that he can see exactly what is going on at all times, and he must be in possession of a script and work in the closest collaboration with the organisers of the various events that are being covered.

The success of a public address system depends largely upon the proper design and subsequent disposition of the elements. The principles of design are well understood, and, in any case, would be outside the scope of a discussion of this nature ; nevertheless it might be worth while to consider some of the considerations involved in the proper disposition of microphones and loudspeakers.

One of the difficulties that confront the engineer is that these installations are temporary, and usually required at short notice. Consequently, there is very little time for consideration of the best method of disposing the equipment. There is no solution for this, and installations can only be planned on a basis of past experience, and modified by trial and error.

I have always found it advantageous to use the basic layout shown in Fig. 10 and to arrange the loudspeakers so that the sound originates from a single point. Wherever it has been necessary to disperse loudspeakers, I have tried to arrange that the distance between any loudspeaker and the audience is similar, and in this way avoid confusion due to the different arrival times of the amplified speech to the listeners.

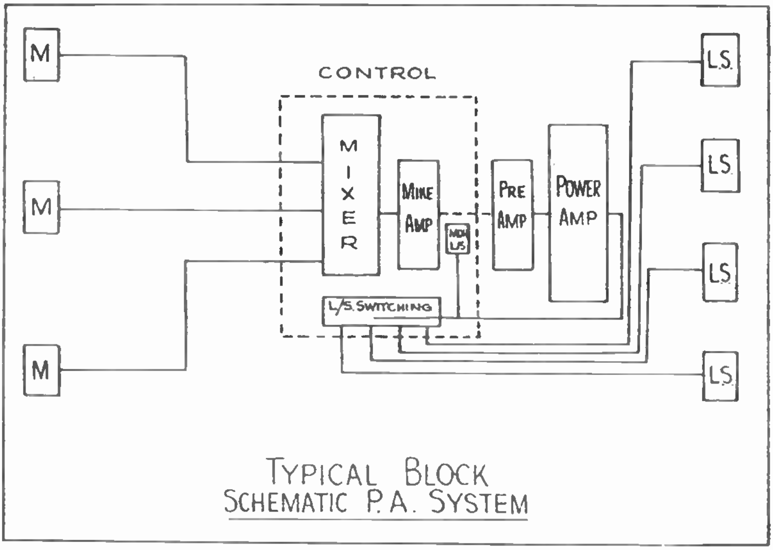

Fig. 10.—Shows in block schematic form the essential elements of any worthwhile public address system.

It is possible to operate microphones directly in the soundfield of the loudspeakers, provided the distance is of the order of 75 to 200 yards, and under these conditions, adequate gain for perfect intelligibility of speech at 500 yards from a battery of horn loudspeakers is quite easy to obtain before feedback ensues.

Making use of the directional characteristics of the velocity ribbon mike in the manner already described improves this result considerably.

As each installation presents a different problem, the following illustrations show the disposition adopted for the equipment in some recent work I have carried out.

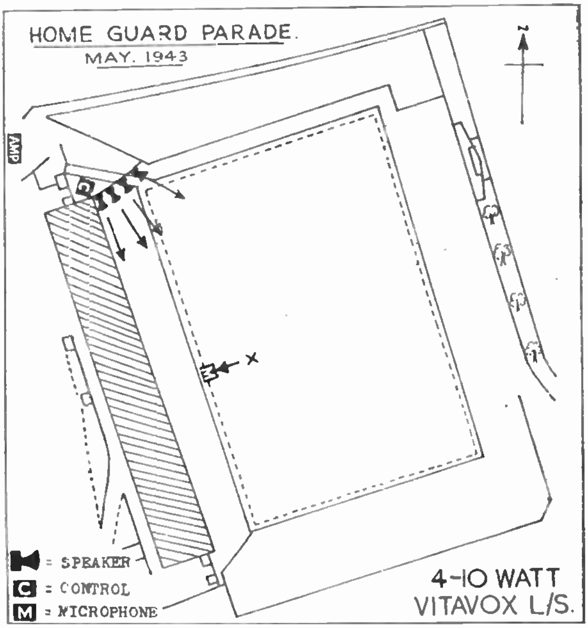

Fig. 11

Fig. 11 shows the distribution of the basic elements adopted to address 5,000 men on a northern football ground. Four 10 watt triple exponential horns were used, fed from an amplifier capable of delivering 100 watts at 5 per cent. total voltage harmonic. Reverberation, which was particularly troublesome in this ground, was greatly improved by the introduction of bass taper to an extent of some 10 dB at 500 cycles.

Fig. 12 illustrates a more powerful and comprehensive installation in the same ground. In this case, the reproduction of orchestral, vocal and spoken dialogue from the stage at the end of the ground was necessary, and in consequence the same degree of bass taper could not be tolerated. The loudspeakers were accordingly repositioned to avoid some of the obstacles that were considered to have given rise to the most serious reverberation on the first occasion. The resultant distribution was very satisfactory.

Microphones suspended on booms were provided for the orchestra and a three-channel fader, enabling a moving coil microphone to be mixed directly with two pick-ups, was provided at the control position for the running commentary, and incidental sound effects.

The six 25-watt exponential horns used on this occasion were driven by an amplifier capable of delivering 450 watts of audio frequency power for 5 per cent. total voltage harmonic content. A mobile 6 kvA petrol-driven set was installed to supply power, as no mains supply could be made available.

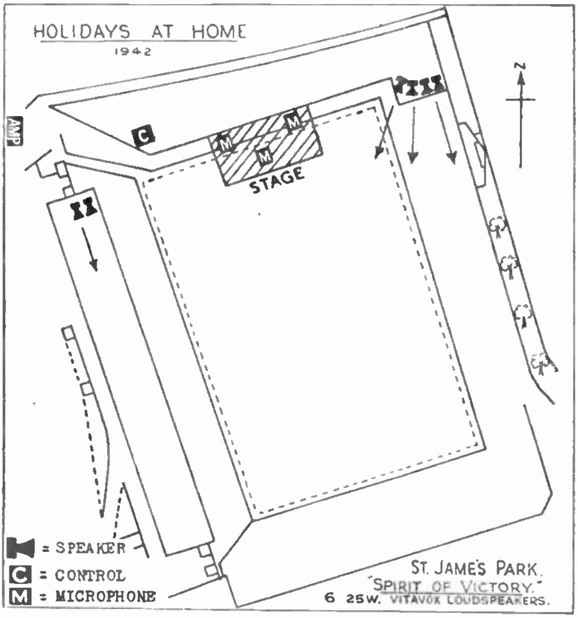

Fig. 12.

Fig. 13 shows a layout where distributed loudspeakers had to be used; three microphone positions were provided and operated in conjunction with a mobile control unit. Two separate and distinct channels enabled running commentaries on events in the Sports Stadium to be made whilst music was distributed to the other loudspeakers on the ground. Two separate power amplifiers supplied 100 watts to each channel serving up to twelve 6-watt speakers at will. Separate speech input equipment for each channel in the mobile control enabled two items to be covered simultaneously.

Finally, Fig. 14 is the diagram of a large job where 50,000 people had to be served in one arena. The occasion was the Silver Jubilee in 1935, and in addition to providing microphone facilities on the ground, it was necessary to radiate the speech of His Late Majesty, King George V, to the assembled crowd. Eight 20-watt moving coil loudspeakers with 7 ft. 6 in. horns were used, erected upon a scaffold in the position shown in the diagram. These speakers were served by a 450-watt amplifier, and microphones were used directly within the soundfield of the loudspeaker battery. Nevertheless, adequate amplification was obtained before the "singing" point was reached, to serve the entire ground.

The special broadcast was received by landline and fed directly into the speech input equipment mixer so that broadcast items and local announcements could be superimposed.

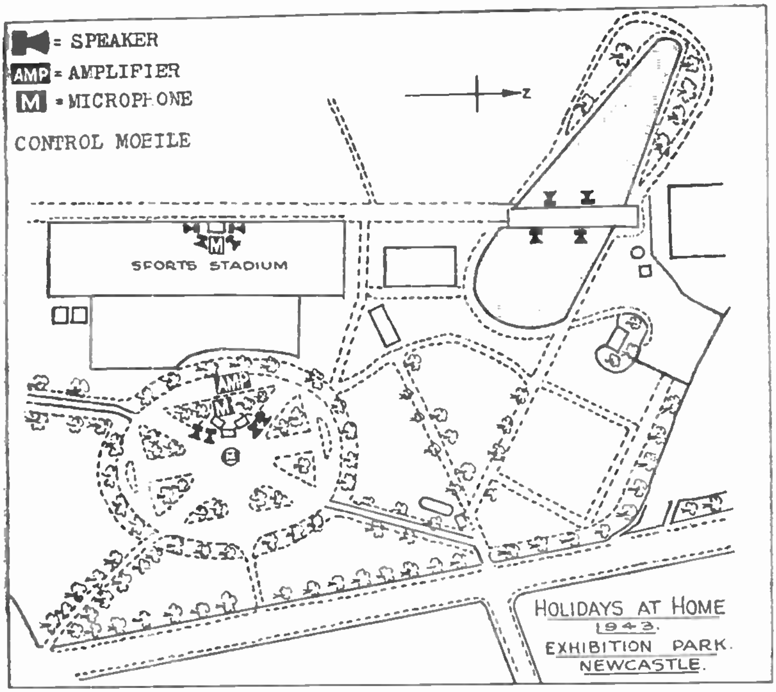
= SPEAKER
AMP = AMPLIFIER
M = MICROPHONE
CONTROL MOBILE
Z
SPORTS STADIUM
M
AMP
M
HOLIDAYS AT HOME
1943.
EXHIBITION PARK.
NEWCASTLE.

Fig. 13.

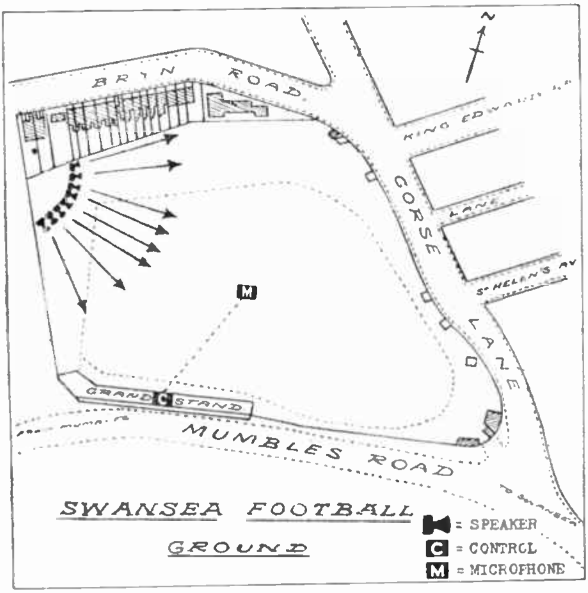
N
BRYN ROAD
KING EDWARD'S RD
LANE
GORSE LANE
ST HELEN'S AV
M
GRAND C STAND
MUMBLES ROAD
TO SWANSEA
SWANSEA FOOTBALL GROUND
= SPEAKER
C = CONTROL
M = MICROPHONE

Fig. 14.

There is no time to discuss in detail the various types of loudspeaker available for public address work. It will be greatly appreciated that the use of exponential horns makes it necessary to sacrifice bass response, but this, in itself, is not an insurmountable objection, where the reproduction of speech is concerned, as high frequency response is more important from the point of view of intelligibility.

Where music and sound reinforcement is required, however, the later type of reproducer, consisting of an open cone radiator for the reproduction of low frequencies, combined with multi-cellular exponential flares, driven by a small diameter diaphragm for the reproduction of high frequencies, appears to achieve a very high standard of quality.

With this type of instrument, the audio frequency power is separated by filters, so that all the energy below 300 cycles is fed to the cone, and everything above 300 cycles to the multicellular horns.

In conclusion, I should like to urge the use of more line input sources for public address. The use of a high fidelity line input in conjunction with the talking picture equipment in a cinema, for example, gives a result which is exceedingly pleasant for the listener, and the author has reproduced many broadcasts of national importance to cinema audiences in this particular way. The same technique is useful for serving overflow meetings, where the audience is remote from the speaker.

NEWCASTLE DISCUSSION

Mr. Clayton (Associate Member) :

I think I would like first of all to thank the authors for the really excellent production ; I must admit it is rather difficult to produce questions covering anything that has not already been covered.

With regard to Mr. Cross's remarks about loss of L.F. due to exponential horns, in the illustrations of the system used at the 31st International Eucharistic Congress, a curved horn is shown, with a cut-off at 56 cycles. I notice that this was used for organ reproduction, but where speech was being reproduced for the massed audience, I think an exponential horn with a cut-off of about 300 cycles was used.

Mr. Cross's photographs were very interesting—especially with regard to local events which we have had occasion to see and hear for ourselves ; and I must say that the Holidays at Home installation, for instance, was remarkably good.

With reference to Mr. Brennan's remarks, he says here " if the system can be made satisfactory in an empty auditorium by suitable acoustic treatment, the results will be much better when the auditorium is filled." That is not necessarily a fact, because, as far as permanent installations are concerned, acoustic treatment is usually made to give best results with about one-third of the audience, the idea apparently being that you never get the theatre filled. Also, in wet weather, when people enter a hall, they have very much more absorbing properties than when they are dry, and it is remarkable what a difference that makes from the point of view of gain required. In a fairly empty hall a gain of 3 dB will be necessary if the people are wearing wet clothes, and if the hall is full, an increase of as much as 5 dB is required.

Mr. Hodgson :

I should like to pay tribute to the very able way in which the authors have prepared and delivered this paper. I agree with the last speaker that there is very little that one can say about it.

In connection with reverberation, which was mentioned in an early part of the paper, I came across one particular case where reverberation was extremely difficult, and I found that since it was mainly a function of the lower frequencies, we could vastly improve the intelligibility of speech by eliminating everything below 1,000 cycles.

Another point ; that is, the question of pre-amplifiers. Like the authors, I find that a battery pre-amplifier is very frequently advisable, in order to keep the background hum absolutely to a minimum. It is possible to use a mains driven type of pre-amplifier with care, but if the background has got to be absolutely negligible, then the battery type is superior.

Mention has been made of horn loudspeakers, and the advantages of the bass cut due to the short horn, the loading of the horn not being sufficient for the lower frequencies. If you use an amplifier which has a straight line characteristic, and you feed horns with this inadequate damping at the lower register, then the diaphragm of the speaker is definitely over-driven, and rupture and damage to the diaphragm may occur. If you have horns with a cut-off of 500-700 cycles, it is advisable to make the amplifier also have a cut-off at 500-700 cycles, otherwise you may wonder why the diaphragms do not last as you expect them to.

Mr. Brennan (replying) :

Cutting out the frequencies below 1,000 cycles would not spoil the intelligibility of speech ; cutting out below 500 cycles makes no appreciable degree of difference in the articulation, and it certainly helps to cut bass if you have trouble with reverberation.

Regarding battery pre-amplifiers, I think Mr. Hodgson is quite right. Working with a microphone of very high impedance, it is essential to use a battery pre-amplifier, if possible, because it does help to reduce the possibility of hum. Cutting out the reproduction of all below 700 cycles will prevent rupture of the diaphragm in cases where very short horns with a cut-off at that point are being used, because otherwise, as Mr. Hodgson says, the diaphragm might be damaged.

Mr. Senior :

I have greatly enjoyed the discussion, and profited by it. There are one or two things I have rather disagreed with, but perhaps that is a point of view, or shall we say, a matter of opinion.

Coming to the question of visible control of microphones ; for my own part—and I have had a little experience in this connection—I would much prefer to be hidden. The effect on a large congregation of people, when they see somebody doing something, is to detract attention from the speaker, or whatever is happening, and you become a centre of interest, and perhaps amusement. With a good script, and careful liaison with the organisers, I would much prefer that the control should be out of sight.

Secondly, I refer to a remark by Mr. Cross about the mixing of microphones with pick-ups. I think Mr. Cross prefers the amplifier to raise the level of the microphone to equal that of the pick-up. I would do the reverse—have an attenuator in the pick-up to make the two levels equal.

Pre-amplifiers, for my own point of view, I do not advocate. With careful screening and balanced lines from the microphone to the mixer, amplification after mixing, I think, is much to be preferred.

Mr. Cross (replying) :

I think Mr. Senior and I are substantially in agreement ; so long as Control can see what is going on I would have no objection to them being invisible to the audience.

There is absolutely no reason at all why you should not attenuate the pick-up to the microphone level, providing the impedance levels are right. When making this point in the paper, I was considering the case where a high impedance microphone was used with soundhead amplification. Under these conditions it probably would be necessary to attenuate the microphone output before mixing.

BIRMINGHAM DISCUSSION

In the absence, through illness, of the Chairman of the Section (Mr. J. Nelson), Mr. W. W. Smith (Hon. Secretary) presided.

Dr. W. Wilson :

The papers we have just heard are very welcome, as the scientific treatment of public address schemes is badly needed. I should like to refer particularly to their use indoors, where, after all, most of us meet with them in about nine cases out of ten. Now every existing auditorium, whether it be town hall, lecture hall, theatre, or church, has been designed with a view to one invariable limitation, namely, that it must not be so large that a single speaker cannot be distinctly heard in any part of the interior. The task that we modern engineers have to carry out is, therefore, to make what should be satisfactory conditions somewhat more perfect, by giving extra power to deal with cases of bad diction, deafness, or faulty acoustic properties. Unfortunately it is very frequently the case that the added apparatus does its work so poorly that conditions are made worse, at any rate as far as some of the audience are concerned, and this is recognised by the authors. For example, some of the audience may find themselves in a "deaf" area, through interference as shown in Fig. 5, while others may be listening to a speaker directly in front of them, and hear his voice coming from over their shoulders or behind their heads. Where the speaker is not present in the building there seems to be no difficulty, as the loudspeakers are placed in the logical position, that is, on the platform in front of the audience ; and I personally have known this arrangement provide a more audible performance than the original speaker could have done. But when the speaker himself is present, those responsible for the layout seem to think it necessary to distribute the loudspeakers about the hall, thereby introducing the serious defects to which I have referred. I noticed that all the diagrams shown by the authors had the loudspeakers concentrated and I should like to ask them whether it should not be the invariable rule that they should be arranged in this way, and should also be as close to the actual speaker as is consistent with the avoidance of acoustic feed-back. The ideal location would seem to be immediately over the speaker's head, and sufficiently in front of him to avoid their output reaching the microphone.

As regards outdoor installations, I consider that the same rule should be observed wherever possible, and this again seemed in accordance with the examples shown by the authors. Several schemes were, however, exhibited in which enormous audiences had to be reached, extending over quite a wide area, and it is well understood that the conditions then are different and require a distributed output.

I should also like to agree with what has been said as regards the importance of a rehearsal either on the actual site or else in a room as nearly similar to the latter as possible. The temptation is to try out the apparatus in a small enclosure, where the result seems almost deafening, but when it is transferred to the larger auditorium filled with people, the volume turns out to be insufficient, and the circuit has to be overstressed, with resulting distortion. A further point I should like to raise as regards fidelity is that the result of speech reproduction should be judged by an elderly man rather than a young one. Intelligibility is the great requirement for a spoken address, and this depends very largely on the full value being given to the high frequency components, that is, the consonants ; and it is well known that the human ear becomes less sensitive to these high frequencies with advancing age.

Mr. Cross :

In a theatre, the work of sound reinforcement aims at enabling everyone to hear clearly without being conscious of a loud speaker. Whilst the loud speakers should be situated in close proximity to the actual speaker, Dr. Wilson has indicated the difficulty of feed-back. Rehearsals should take place under conditions comparable with those in which the apparatus is to be used—in the same room if possible. A point to be borne in mind is that, usually, rehearsals take place in an empty room. An audience made a big difference to reverberation, which would also be greatly reduced by the presence of wet clothing.

With regard to high fidelity reproduction, it was true that the individual response of different people's hearing made the question of high fidelity reproduction a difficult one to define. There was an unfortunate trend, in receiver design particularly, to make people's appreciation of high fidelity reproduction not quite so good as it should be ; usually, receiver design was a compromise between the requirements of selectivity and quality. Few appreciated good reproduction.

Mr. Brennan :

The aim should be to get the resultant intensity of the direct sound and reinforcing sound as uniform as possible and the reinforcing sound should come from a position close to the speaker. Further, it should not be as strong as the actual strength of the speaker's own sound. If anything, it should be less, so that wherever the listener was his ear was attracted first of all by the sound from the speaker himself, rather than by the sound which was supporting the speaker. Arrangement in indoor places could ensure that resultant intensity was very uniform.

With regard to high fidelity reproduction a line must be drawn to distinguish between high fidelity and intelligibility. Intelligibility was always necessary ; high fidelity reproduction was not always necessary. As to the cutting out of the bass, the cutting out of frequencies under 750 cycles a second left about 90 per cent. of the interpretation, and the cutting out of frequencies under 1,200, 80 per cent. Older people would be able to distinguish a reduction in the high frequency range. Articulation was the important thing.

Mr. F. H. Alston (Associate Member) :

The actual response at the lower frequencies would not fall to such an extent with an elderly person whose hearing was rather lacking in the higher frequencies. With an elderly person, the loss at 50 cycles was practically negligible, so that the curve remained flat at a much lower frequency. On the other hand, towards the higher frequency above about 3,000 cycles the curve fell rapidly, and at 4,000 it was quite flat.

With normal hearing a small rise also occurred, but with normal hearing at 50 cycles it fell to zero.

DISCUSSION

Mr. Brennan :

The measurement of loudness was a rather difficult problem, because there were enormous variations in the sensitivity of quite a large number of people. Therefore, unless tests were made with a large number of people, it might be misleading to say that any particular curve represented the average.

Mr. Kenworthy Brown (Visitor) :

There is a resonance point in the sensitivity of the human ear. Was this a matter of resonance to some frequency in the ear ?

Reference had been made to peak limitation in order to economise in power, suggesting a straight line output characteristic up to a certain level, and then more or less flattening it off so as to avoid excessive peaks. It seemed that for certain kinds of jobs it would be an advantage to have a more smooth compression of volume range over the whole scale of volume so as to give the speaker more latitude in moving his head away from the microphone. Did an exponential and a Tractrix horn of about the same size, when tested, show a noticeable difference in the results ?

Mr. Cross :

The problem of the human ear was physiological. There was a series of tiny threads in the inner ear each of which was attuned to a particular frequency and vibrated under the pressure of a particular frequency of sound wave on the ear drum. The agitation of the selective thread gave a particular sense stimulus which was recognised as a frequency of sound. In an older person, due to some failure in the nervous system, response to the higher frequencies might fall off.

Mr. Brennan :

At low frequencies a Tractrix horn gives better results than an exponential horn. The length of an exponential horn had to be very great indeed to develop fully the lower frequencies.

Vote of Thanks :

North-Eastern and Midlands Section members gave an enthusiastic vote of thanks to Messrs. H. Brennan and A. Cross.

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(6) "Speech Power and its Measurement." L. J. Sivian. *Bell System Technical Journal*, Vol. 8, p. 646.

(7) "Power and Realism." G. E Morrison. *Wireless World*, June 1942.

(8) D. A. Oliver. *Journal of Scientific Instruments*, Vol. 7, No. 4, April 1930.

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MEMBERS' MEETINGS

London Section.

A special meeting will be held on Wednesday, February 16th, 1944, at 6.30 p.m., for a discussion on :

Television Standards.

The discussion will be opened by
L. H. Bedford, O.B.E., M.A., B.Sc. (Member)
and
W. A. Beatty (Member)

The Council invite members to prepare contributions for discussion at the meeting.

Ordinary meetings will also be held on February 24th and March 10th (not March 30th as previously announced) at 6.30 p.m.

All these meetings will be held at 11, Upper Belgrave Street, London, S.W.1.

Midlands Section

The following meetings will be held at The University of Birmingham (Mathematics Theatre), Edmund Street, Birmingham :

Tuesday, February 29th, 1944 :

" Electronics in Medicine "

A Paper by
G. Parr (Associate Member).

Friday, March 31st, 1944 :

" Some Aspects of Special Electron Tubes."

A Paper by
F. E. Lane (Associate Member).

Ordinary meetings will also be held on April 25th, May 23rd and October 3rd, 1944.

North-Eastern Section.

The following meeting will be held at Neville Hall, Newcastle-on-Tyne :

Wednesday, March 1st, 1944, at 6.30 p.m. :

" A Review of Wide Band Frequency Modulation Technique "

A Paper by
C. E. Tibbs (Associate Member)

Wednesday, March 22nd, 1944, at 6.30 p.m. :

" Relaxation Oscillators and Trigger Circuits "

A Paper by
Emrys Williams, Ph.D.

Ordinary meetings will also be held on April 26th and May 24th at Neville Hall.

The

British Institution of Radio Engineers

NOTICES

(*These have had to be omitted from recent Journals because of paper restriction*)

: :

Obituaries

The General Council regret to record the deaths of the following members of the Institution :—

Sir William Noble, Senior Vice-President. A native of Aberdeen, Sir William Noble began work in the Post Office Telegraph Department of that town in 1874. At the age of 32 he was made Post Office Engineer for North-East Scotland but was subsequently transferred to London and earned promotion to various appointments until he became Engineer-in-Chief to the G.P.O.

He gave a great deal of time to research and development in telecommunication technique, both in Great Britain and abroad. He was awarded a Knighthood in 1920, and in 1922 he resigned from the Post Office and joined the Board of the General Electric Company Ltd.

He was then closely associated with the formation of the British Broadcasting Company and was, in fact, one of its first directors. It was about this time that he first became interested in an institution for radio engineers in Great Britain and was associated with the first association of this kind, the British Radio Association. From this Association developed the Institution as we know it to-day, and for his services to the science and for his encouragement and help in the work of the Institution, Sir William Noble was elected a Vice-President in 1931 and made an Honorary Member in 1932.

Although he had been ill for the last two years, Sir William Noble kept in regular communication with the Institution until his death on November 9th, 1943, at the age of 82 years.

Murdock MacLennan, of Giffnock, Renfrewshire (Member). Elected an Associate Member in November, 1933, Mr. MacLennan had been associated with the Glasgow Education Authority since 1924 as a lecturer, and latterly as supervising lecturer in radio engineering. During the first two years of his appointment, he was engaged on radio-therapy research work under the Beit Research Committee. He was transferred to Full Membership in September, 1928, and served on a number of Committees dealing with radio training, radio engineering and radio service work examinations. Mr. MacLennan passed away on the 24th September, 1943, at the age of 48 years.

George Stanley Chambers, "Markath," Egerton Close, Wiltshire Lane, Eastcote, Middlesex. Elected an Associate of the Institution in March, 1938, Mr. Chambers had worked with the Philco Radio Corporation, Limited, since 1935, and just prior to his death had lodged a proposal for transfer to Associate Membership. His death at the age of 32 years was the result of an accident whilst engaged on Home Guard duties.

Leonard R. Tonkin, 73 Derwent Avenue, East Barnet. Although only elected an Associate Member in October, 1942, Mr. Tonkin had been interested in the work of the Institution for a number of years and was a frequent visitor to London Section meetings. He passed away on the 20th July after a very short illness at the early age of 29 years.

William Cummins, 4 Serpentine Road, Ballsbridge, Dublin, was registered as a Student member of the Institution in March, 1939, and during the past year had been employed in England. After a very brief illness he died in Birmingham, during May, at the age of 30 years.

John Westacott-Davis, 11 Hill View, Henleaze, Bristol. Registered as a Student in December, 1941, reference to Mr. Westacott Davis was contained in the September-November 1942 Journal when it was reported that he was missing after the battle of Singapore.

He is now known to have died, at the age of 22 years, whilst a prisoner in the hands of the Japanese only a few months after his father died in Bristol as a result of enemy action.

John Westacott Davis enlisted in the Royal Artillery before the outbreak of war and was an only son.

Ronald Vernon Lister, of Millgarth, Harcourt Street, Heworth, Yorks. Registered as a Student member of the Institution in February, 1939, Mr. Lister enlisted in the R.A.F. at the commencement of hostilities and was made a prisoner of war in Japan early in 1942. Letters were exchanged with him in the Java Camps, and it was with deep regret that advice was received in December, 1943, that he had died whilst a prisoner of war, at the age of 27 years.

Gifts to the Institution's Library

The General Council acknowledges with thanks donations of books and proceedings from Flight Lieut. E. V. Jacobs and Mr. E. Cattanes (Members), and Mr. W. F. Dalton (Associate Member).

Through the generosity of Mr. Cattanes, the Institution has acquired 16 volumes (1917 to 1927) of *R.G.E.* (*Review Générale d'Electricité*) and 4 volumes (1923 to 1927) of *Electro Tecnica* (Journal of the A.E.I.).

Bound Volume 3 (New Series) of the Journal

This issue of the Journal (No. 7) completes Volume 3 (New Series). Paper restrictions have prevented the Institution from retaining in stock a large number of past issues, so that bound volumes of Volume 3 cannot now be purchased. Bound copies of Volume 2 also are no longer obtainable, but a few copies of Volume 1 may still be purchased for 12s. 6d. post free.

A limited number of bindings of the present series (Volume 3) can be undertaken and members who wish their issues to be bound by the Institution's printers should return all single copies to the Institution accompanied by a remittance of 7s. 6d.

A contents index for the present volume is given on page 328.

New Elections to Membership

Commencing with the March/April 1944 Journal (Volume 4, New Series), the General Council will resume the practice of publishing new elections.

The first list will cover elections subsequent to publication of the Year Book, a copy of which will be sent to every member of the Institution by the end of March.

Parliamentary and Scientific Committee

Under the ægis of the Parliamentary and Scientific Committee, comprising Members of both Houses of Parliament and representatives of scientific and technical institutions, a report has been published on " Scientific Research at the Universities of Post-war Britain." Part 1 of the report deals with the need for increased research in Great Britain ; emphasis is laid on the work of industrial research associations and mention is made of the Institution's proposals for the formation of a British Radio Research Institute.

Part 2 deals with the supply and training of research personnel and recommends steps to be taken to provide facilities for education in graduate research work. It also advocates the foundation of Chairs in Aeronautics and Radio Engineering in the Universities.

Copies of the report may be obtained from the Institution, price 6d. post free.

International Conference of Radio Institutions

Since Sir Ernest Fisk left England, a letter has been received from the Australian Institution stating that their Council supports the idea of an early Post-War International Conference of Radio Institutions to be held in England.

Although there are many difficulties to be overcome, the proposal is generally well supported, particularly in view of the need for early post-war international discussions and arrangements. The Institution's proposal has also been addressed to the American Institute of Radio Engineers.

Honours

The Council has tendered congratulations to Group Captain Sidney Lugg (Member) on his recent appointment as a Commander of the Most Excellent Order of the British Empire.

British Radio Research Institute

The Council has approved a proposal of the Parliamentary Committee of the Institution recommending the formation of a British Radio Research Institute. The proposal has been addressed to the radio industry and to the Government. It will be printed in full in the next issue of the Institution's Journal, but members who wish to discuss the proposal in their firms can obtain separate copies of the pamphlet outlining the proposal by applying to the Secretary.

Sir Ernest Fisk Elected an Honorary Member

Following his address to the Institution, Sir Ernest Fisk attended a meeting of the General Council of the Institution on September 16th, 1943. The occasion was marked by Sir Ernest receiving the Certificate to mark his election as an Honorary Member of the Institution, minuted by the General Council at their July 1943 meeting.

A Vice-President of the British Empire Society, Sir Ernest Fisk has on numerous occasions been honoured in appreciation of the services he has rendered in Australasia and for the British Commonwealth in the field of radio communication.

Further tribute to his work has been marked by his appointment, in February 1944, as an Honorary Member of the Institution of Electrical Engineers.

Companions of the Institution

The Membership Committee have proposed that, in accordance with the Bye-laws and Articles of other professional bodies the Institution should provide for the association of those engaged within the radio profession but not in a technical capacity. The General Council are, therefore, proposing at the next Extraordinary General Meeting, the inclusion of the following Article, in order to provide for the election of Companions :—

COMPANIONS

> " Admission to the grade of Companion is at the discretion of the General Council. Every candidate for election to this class shall be not less than thirty-five (35) years of age and rendered such important services either :—
>
> (*a*) To radio engineering, but not necessarily in a technical capacity ; *or*
>
> (*b*) Obtained such responsibility in the radio industry that his election as a Companion would be of benefit to the Institution."

The

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GRADUATESHIP EXAMINATION.

Seventy-four candidates entered for the November, 1943, Examination which was held in 14 centres in Great Britain and abroad. A few papers from overseas centres have not yet arrived and a supplementary list will, therefore, be issued later. It is, however, apparent that the great majority of candidates failed to obtain adequate marks for even one subject, and the report of examiners on the papers written will be included in a review of examination work which will be published in a forthcoming issue of the Institution's Journal.

PASS LIST—NOVEMBER, 1943

Passed entire Examination

Bazin, Rene E.	Harold Wood
Biram, John G. S. (S.)	Hindhead
Darlington, Edwin G.	Gibraltar
Gwynn, Norman T. (S.)	Twickenham
Hughes, George E.	West Molesey
Jones, John W. (S.)	London, N.W.8
Prevost, Paul J. C.	Croydon
Rae, Donald (S.)	Carlisle
Reece, Charles N. W. (S.)	Manchester
Shaw, Granville L. (S.)	Long Eaton
Spencer, Herbert C.	Guildford
Twiddy, Norman D.	London, S.W.12

The above list includes Candidates who are exempt from, or who have previously passed a part of the Examination and who have now passed the remaining subjects.

The following Candidates Passed Part 1 only

Mager, Basil B. (S.)	London, N.13
Russell, Eric V. (S.)	Buckingham
Turner, Cycil (S.)	Manchester

The following Candidates Passed Part 2 only

Andrew Laurence (S.)	Brighton
Huth, Pavel H. (S.)	London, W.9
Osborne, John L.	Cheam, Surrey

Peck, Charles O. (S)	Welwyn
Pratt, Charles A. (S.)	Croydon
Tomalin, Norman H. (S.)	Rugby
Turner, Peter F. (S.)	London, E.10
Zelinger, Geza (S.)	Haifa

The following Candidates Passed Parts 1 *and* 2 *only*

Smith, Granville	Henlow
Trevor, Patrick F. (S.)	London, S.W.12

The following Candidates Passed Parts 2 *and* 3 *only*

Ithell, William E. (S.)	Enfield
Oliver, Leo F. (S.)	Weymouth

The following Candidates Passed Parts 2 *and* 4 *only*

Copestick, Leslie B.	Surbiton
Doherty, Edmund J.	London, S.E.22
Dorey, Peter F. (S.)	Daventry
Garrett, Harry (S.)	Hindhead

May Graduateship Examination

The next Graduateship Examination will be held on May 19th and 20th, 1944, and the closing date for receiving applications is March 31st.

Arrangements for the examination have already been made in the following centres :

London, Wolverton, Manchester, Birmingham, Cairo, Calcutta, Bombay, Ceylon, Jerusalem.

Copies of Past Examination Papers

Only copies of papers set in November 1942 and May and November 1943 examinations are now available. Papers set in examinations from 1929 to 1941 inclusive are now out of print, and it is not intended to reprint them. Members and Students of the Institution may, however, borrow copies of these past papers from the Library.

Radio Trades Examination Board

The first Radio Servicing Certificate Examination to be held under the auspices of the Board will take place on Saturday, May 13th, 1944. The closing date for receiving applications, which should be addressed to the Secretary to the Board, must be lodged not later than March 31st.

The examination comprises a three-hour practical test and a three-hour written paper. A detailed syllabus of the examination can be obtained on application to the Secretary, 9 Bedford Square, London, W.C.1.

The
British Institution of Radio Engineers

(Founded 1925. Incorporated 1932)

9 Bedford Square, London, W.C.1

JOURNAL

VOLUME 3 (New Series), 1942—Jan. 1944

CONTENTS *Pages*

BOOK REVIEWS

Testing Radio Sets. By J. H. Reyner, B.Sc., A.C.G.I., D.I.C., A.M.I.E.E.

Readers who are familiar with the earlier editions of this book will find that, while the sections dealing with instruments generally have been very greatly expanded and brought up to date, the remainder of the book, which is mostly concerned with tests, and necessarily involves a considerable amount of reference to receiver design, can almost be said to have been " lifted " solidly from the earlier editions.

After a very elementary introduction, the author reviews in two very good chapters the salient points in volt/ammeter and signal generator design, with photographs of modern commercial instruments. The subject is pursued in the same manner in a later chapter on " Component Testing", and in the writer's opinion these three chapters are the best in the book.

The intervening chapters cover set testing generally : Audio Frequency, Tuning, Radio Frequency, Superhet, Mains, Short Wave, Receivers. They contain useful information, but on the whole they give the reader the impression of having been rather hurriedly revised for this edition. The use of the original diagram blocks, where they are applicable, is to be commended, particularly in war-time, but in some cases, where the vintage is perceptible, there is a strong flavour of the very early thirties. Some which are described as " typical " are decidedly out of date.

While there are many points of interest in the context, some important items are glossed over very lightly, while others are omitted altogether. A.V.C., although references to it occur in three places, is on the whole dismissed summarily ; such items as tone control, tuning indicators and A.F.C. are omitted entirely.

The book is rounded off with a brief description of the cathode ray tube, an unnecessary chapter on "Some Curious Faults", and two useful appendices : " R.C. Networks " and " Negative Feedback ".

It certainly contains much information that would be useful to the keen service mechanic, particularly as he would already be familiar with modern receiver design. The book is published by Chapman & Hall, 11, Henrietta Street, London. W.C.2, at 15s. net. E. A. W. S.

Radio-Technology. By B. F. Weller, A.M.I.E.E.

The purpose of this text-book is to cover the principles of radio engineering for readers with a reasonable basic knowledge of electricity and mathematics.

The first ten chapters deal with damped oscillations, diodes, triodes and pentodes, power amplifying valves, transmitters for radio telegraphy, radio-telephony transmission, principles of reception, the supersonic heterodyne, aerial systems and radiation. The treatment is mathematical where such a presentation is called for, but considerable attention is devoted to practical aspects, particularly in connection with power amplifiers and transmitters. In general, the subject matter covers part of the syllabus of the Radio Technology and the Radio Engineering papers of the Institution's examination as well as the City & Guilds syllabus in Radio Communication.

The student will be puzzled to read in connection with skin effect on p. 25 " if the current is changing very rapidly . . . it will not have time fully to penetrate the conductor . . ." and again on p. 27 in connection with r.f. inductance, that this apparently decreases with frequency due to the increase in resistance. The connection diagrams of the Hartley and the Colpitts circuits on p. 156 need revision.

The author aims at filling the gap between the popular books and the reference books on radio engineering, and in this he has been highly successful: the volume represents a substantial advance in the literature of the subject and is recommended.

Price 21*s*. net. Library No. 604.

Published by Chapman & Hall, Ltd. E. T. A. R.

Time Bases (Scanning Generators). By O. S. Puckle, A.M.I.E.E.

This book represents probably the first really serious approach to the compilation of a really comprehensive treatment of this very wide aspect of oscillography. There must be very few people who can call to mind any aspect of the subject which is not treated in the book, and the general arrangement of the chapters and the classification could hardly be improved upon.

After the introductory chapter there is a general chapter on Time Base Wave Forms, and the author then passes to more specialised treatment of the various classes of scanning generators.

A number of circuit arrangements covered in chapters 4 and 6 have received scant mention in any other work, and the treatment throughout is most painstaking and explicit. Chapters 7, 8 and 9 are largely devoted to applicational problems, and the final chapter is a very interesting outline of the use of Time Bases for frequency division.

In view of the very large number of incomplete, and in some cases inaccurate, descriptions which have been made of the various features and aberrations present in the cathode ray tube, the first of the seven appendices is particularly timely as the treatment throughout is exemplary, being in all cases brief, accurate and complete, whilst even those who have made extensive use of gas discharge triodes will find much that is new to them in appendix three. The remaining appendices cover differentiating and integrating circuits, the generation of square waves, phase shifting of sinusoidal waves, and the treatment on the effect of large shunt capacitances in anode load circuits.

There are numerous explanatory notes and bibliographic references throughout the text, and there is a short bibliography immediately before the index.

It is hard to see any way in which the book could have been improved, and the author may well feel that he has provided the standard on this subject for a long time to come.

Price 16*s*. net. Library No. 564.

Published by Chapman & Hall. T. D. H.


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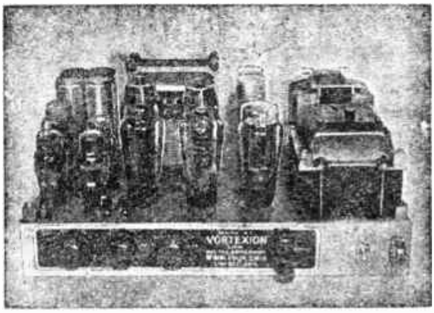

The new Vortexion 50 watt amplifier is the result of over seven years' development with valves of the 6L6 type. Every part of the circuit has been carefully developed, with the result that 50 watts is obtained after the output transformer at approximately 4% total distortion. Some idea of the efficiency of the output valves can be obtained from the fact that they draw only 60 ma. per pair no load, and 160 ma. full load anode current. Separate rectifiers are employed for anode and screen and a Westinghouse for bias.

The response curve is straight from 200 to 15,000 cycles. In the standard model the low frequency response has been purposely reduced to save damage to the speakers with which it may be used, due to excessive movement of the speech coil. Non-standard models should not be obtained unless used with special speakers loaded to three or four watts each.

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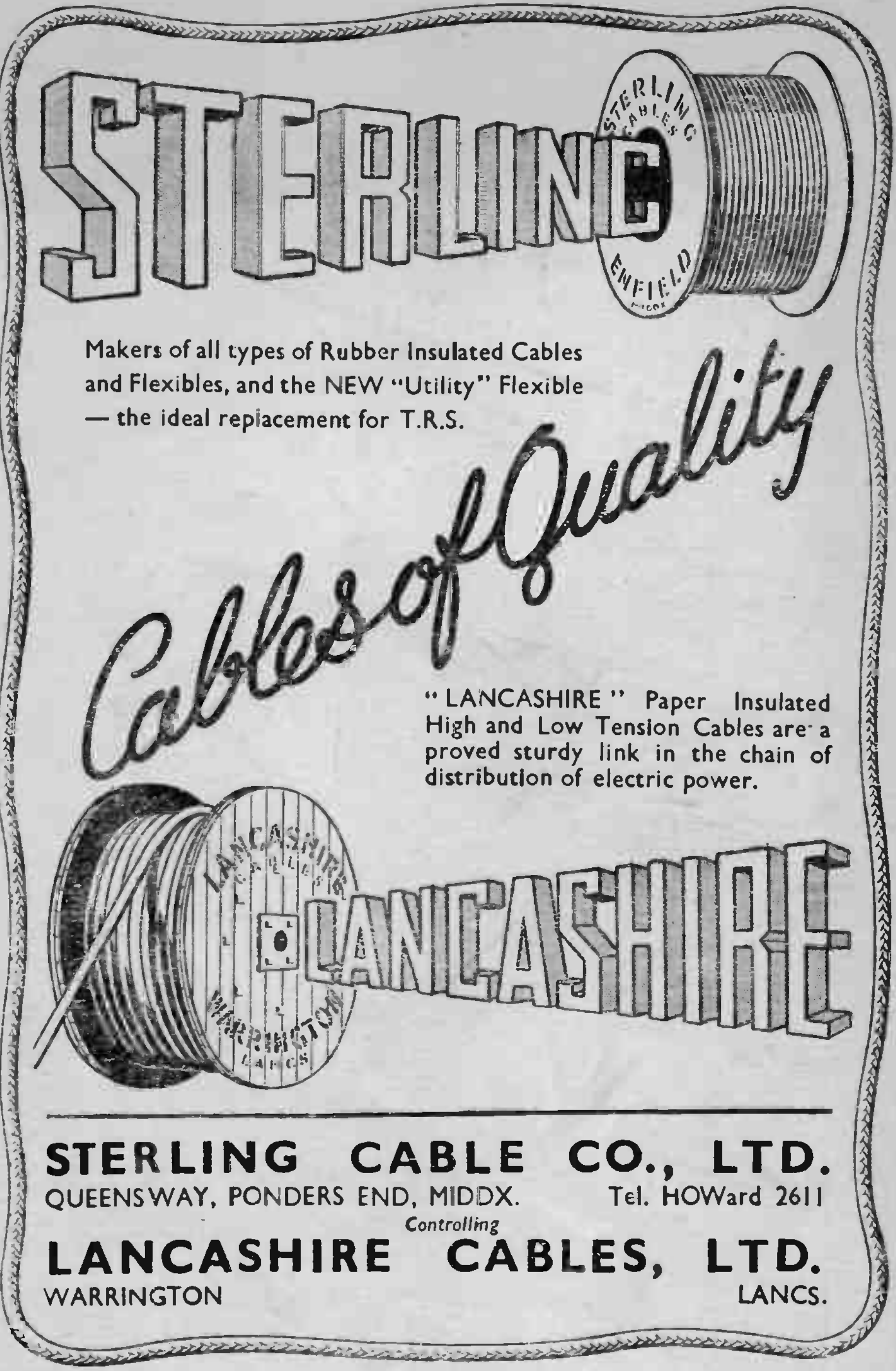

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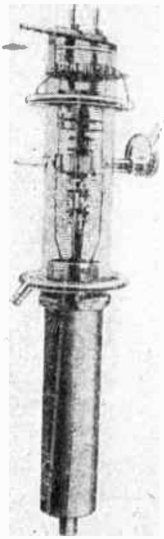

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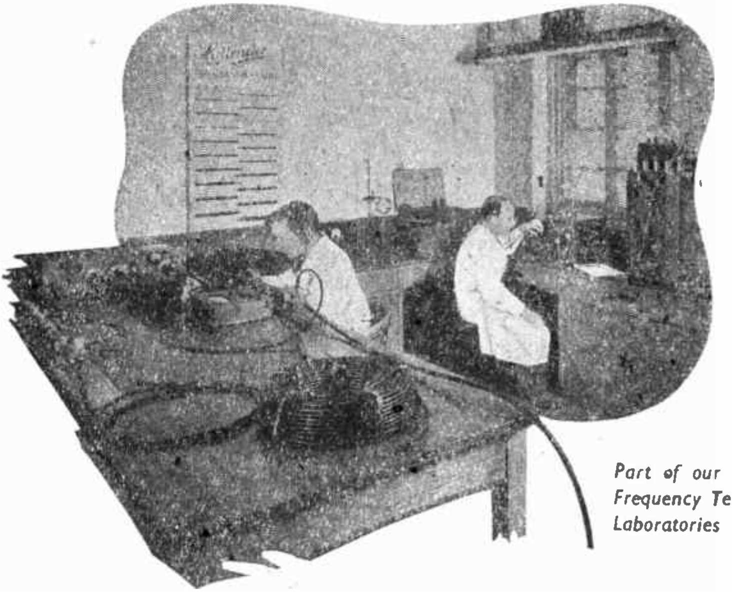

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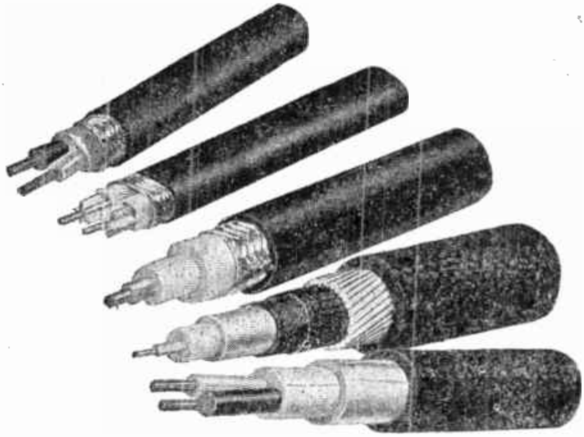

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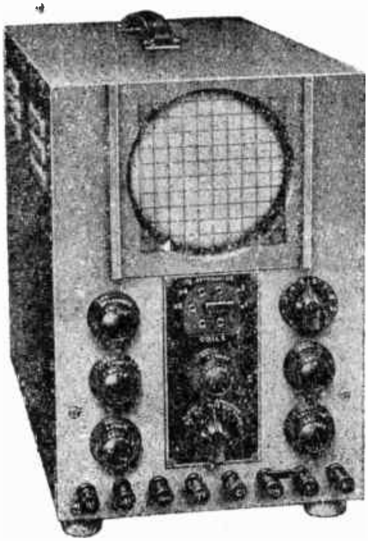

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JOURNAL OF
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Vol. 4 (new series) No. 1 1944. MARCH-MAY, 1944.

" To promote the general advancement of and to facilitate the exchange of information and ideas on Radio Science."

NINETEEN YEARS

Since 1925, the growth of the Institution has been commensurate with the advance of radio science and practice. Scientific progress is always accelerated by the demands of war, and the nature of the present conflict has emphasised the editorial comment made of the Institution 19 years ago, " That it is eminently desirable that those technically interested in Wireless should have some such Institution, nobody will deny."[1]

That specialisation in a particular application of science gives rise to progressive development was the keynote of another editorial written two years before the Institution was founded.[2] The aptness of this comment as applied to radio has been well exemplified, but it is impossible even to maintain the upward slope of the chart of progress without intensive fundamental research. Acknowledgment of this fact has been given by leaders of State and Industry, resulting in recent months by the publication of such reports as are referred to on page 44. More recently, history has been made by the House of Commons devoting a full day's debate to the subject of research and scientific knowledge, when the Lord President of the Council (Mr. C. R. Attlee) said : " Perhaps most striking of all has been the development of radio." (*Hansard* 19/4/44.)

Planning should be so justified as to initiate early, if not immediate, action. The advancement of radio engineering necessitates greater knowledge of the science—a point which is emphasised throughout Part 2 of the Institution's Post-War Development Report which will be published in the next issue of the Journal. An introduction to this Report has taken the form of a proposal to the radio industry and the Government of Great Britain for the formation of a British Radio Research Institute, and for permanent record the proposal is contained on pages 37.

A most favourable reception has been given to the report by Universities, the Government, many individual firms in the Industry

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[1] *Wireless Engineer*, Vol. 2.
[2] *Wireless World*, Vol. 12.

and the general press. Following publication of the Parliamentary and Scientific Committee's report, the Institution's proposal has stimulated thought, and it is understood that through the various associations comprising the Radio Industry Council, the radio industry is considering the organisation of radio research. Apart from the frequent references of the Prime Minister to the future of radio science, stimulus has been provided by the publication of a White Paper on " Scientific Research and Development." It is known that the Government recognises the great importance to the nation of fundamental research in radio, and the Institution's proposal will be of value to the industry and to the Department of Scientific and Industrial Research ; with them must rest the final plan for the formation of an organisation of adequate size to deal with the problems which must be faced to ensure progressive development.

Co-operation

The co-operation between the various bodies representing applied science was typified in the drafting of the Parliamentary and Scientific Committee's Report which preceded the Institution's proposal. The latter recommends that research planning should bring into association representatives of the professional Institutions who are directly or indirectly concerned with radio matters. In addition, therefore, to being sent to the Universities, the Institution's proposal has also been lodged with the Royal Institute of Chemistry, the Institute of Physics and the Institution of Electrical Engineers who are contributors to the development of radio science in much the same way as the Institutions of Mining and Metals contribute to the understanding of Metallurgical science.

Science as a whole co-relates each branch of engineering, and all professional engineering institutions have as their main object the advancement of the particular art which they represent, but co-operate with each other in the matters which closely or nearly affect their main object.

Reports of Progress

Development of any particular science is always evidenced in the publications emanating from that field of endeavour. Evidence of British progress has necessarily to be concealed in times of war; such restriction has as much prevented regular and frequent issue of the Institution's Journal as has paper rationing, which, in turn, leads to printing and make-up problems.

In order to utilise the Institution's paper ration to the best advantage, consideration has frequently been given to altering the format of the Journal in order to accommodate papers available for publication, as well as providing more timely issues. A new format will be adopted in the very near future, but present difficulties have combined to make it necessary for this current issue to cover the first four months of this year instead of two bi-monthly issues.

G. D. C.

The British Institution of Radio Engineers

ANALYSIS OF THE OPERATION OF DOUBLE-CONTROL GRID TUBES

by

G. L. Hamburger (*Associate Member*).*

SUMMARY

In this paper a mathematical treatise is given which permits to calculate conversion transconductance, modulation distortion, crossmodulation, modulation trim and converter whistles from the empirically found static characteristics of the tube. Whilst it is not anticipated that in practice the above-mentioned effects should really be evaluated along the lines indicated in the following, viz., from the static characteristics, the theory thus elaborated offers a clear view and understanding of the manner in which these effects are brought about. Also the theory suggests directions of improving the operational qualities of such a tube by indicating the desirable features of the characteristics. An attempt has been made to illustrate the essential points of the theory and its results by means of a number of figures with short explanatory text in such a way that their preliminary study alone gives to the reader a first survey of the matter.

0. NOMENCLATURE

i_a	plate current.
${}_Aa_\mu$	Taylor coefficients of the characteristic $i_a = i_a(u_I, o)$, i.e. the coefficients of the corresponding power series.
${}_B\alpha_\nu$, ${}_B\beta_\nu$, ${}_B\gamma_\nu$, ${}_B\delta_\nu$	Taylor coefficients of the power series for ${}_Aa_0(u_{II})$, ${}_Aa_1(u_{II})$, ${}_Aa_2(u_{II})$, ${}_Aa_3(u_{II})$.
u_I, (u_{II})	momentary value of the voltage on grid I, (II).
U_I, (U_{II})	amplitude of the voltage on grid I, (II), both referred to their corresponding grid biases.
μ, ν	current indices referring to the Taylor expansion (order of the individeal term).
m_{20}, m_{53}, etc.	coefficients referring to the trigonometric relations (2a).
${}_Aa^*_\mu$	Fourier coefficients of the series for $i_a = i_a(U_I \sin \omega t, o) = i_a(t)$.
${}_B\alpha^*_\nu$	Fourier coefficients for the function ${}_Aa_0(U^I{}_I \sin \Omega t) = {}_Aa_0(t)$ and similarly ${}_B\beta^*_\nu$, ${}_B\gamma^*_\nu$, ${}_B\delta^*_\nu$.
ω, Ω	angular velocities of high frequency.
p	angular velocity of low frequency.
m	depth of modulation.
I_{IF}	amplitude of the IF current.
h_κ	integer factor for the formation of combination frequencies, see equ. (15).
n	number of frequencies impressed upon grid I.

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* Ms. accepted by the Institution, 15th June, 1943.

g_ν	conversion transconductance for the higher IF due to harmonics of the oscillator (21 for $\nu = 2$, 31 for $\nu = 3$, see Fig. 10).
g_c	conversion transconductance for the first IF due to the oscillator fundamental (11, for $\nu = 1$, see Fig. 10).
k	modulation distortion factor.
m_2	depth of modulation of an interfering carrier ω_2 (modulation frequency ρ).
m_1	depth of modulation of the desired carrier caused by cross modulation.
${}_\rho m_1$	as above, but referring to the audio fundamental ρ.
${}_{2\rho}m_1$	as above, but referring to the 2nd harmonic 2ρ, this audio distortion occurring in the course of the process of cross modulation.
c_r	crosstalk factor.
I_1	current amplitude of the fundamental of ω.
g_o	maximum possible slope of signal grid characteristic usually at zero grid voltage.
Ω_W, ω_W	values of oscillator and signal frequency producing an interference whistle in the mixer.
m_W	degree to which the IF carrier is whistle modulated.

1. INTRODUCTION

When the operation of a double-control-grid-tube is investigated it will be found that the problems involved can be divided into two essentially different parts. The first part concerns the electronic mechanism proper and culminates in the predetermination of the tube's characteristic diagrams from electrode structure dimensions. In the second part, however, the tube characteristics are assumed known and the tube's behaviour as a non-linear unidirectional element is examined. This latter part only is to be discussed in this article. Taking the empirically found characterictics as a basis, a method for calculating the mixing process performed by the tube will be elaborated.

2. GENERAL EXPRESSION FOR THE PLATE CURRENT

Since it is not intended to deal with noise problems in this particular treatise, any multigrid tube can be reduced to a double-control-grid-tube of which the following idealisations are assumed :

1. No reaction of the plate voltage upon the electron current, i.e. infinite plate impedance.
2. No interaction between the two control grids.
3. No current is drawn by the control grids.

In accordance with these assumptions the tube is a purely unidirectional device, viz. a constant current source controlled by two grids entirely independent from one another. Its entire behaviour can then be represented by a single family of curves, plotting the plate current against one control grid voltage assigning to the other control grid a parametric value or by a three-dimensional chart plotting the plate-current against both control grid voltages thus obtaining a curved surface. (Fig. 5.) It will be seen at once that the two grids are essentially of equal significance. (In this article

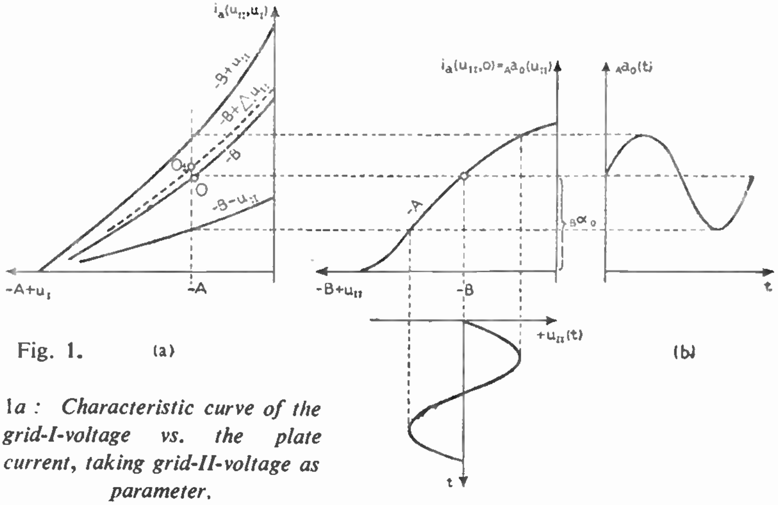


Fig. 1.

1a : Characteristic curve of the grid-I-voltage vs. the plate current, taking grid-II-voltage as parameter.

1b : Variation of the plate current with grid-II-voltage, applying to grid I the bias minus A. Varying grid-II-voltage sinusoidally produces a variation of the plate current with time according to the ${}_Aa_0(t)$*-curve.*

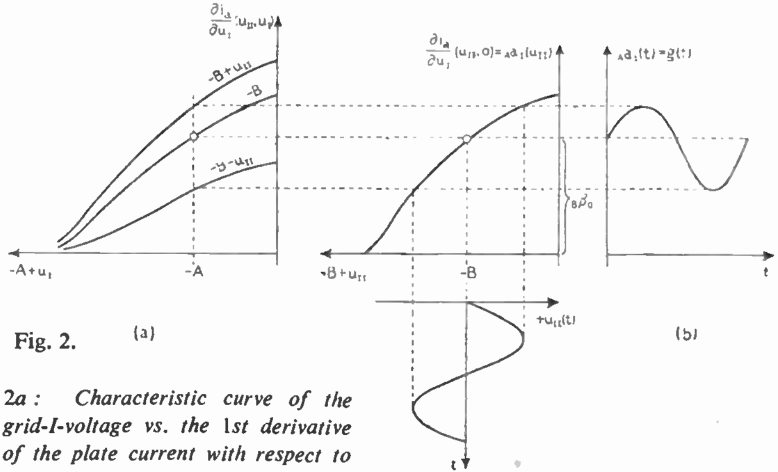


Fig. 2.

2a : Characteristic curve of the grid-I-voltage vs. the 1st derivative of the plate current with respect to grid-I-voltage, viz. vs. the slope, taking grid-II-voltage as parameter.

2b : Variation of the slope with grid-II-voltage, applying to grid I the bias minus A. Varying grid-II-voltage sinusoidally produces a variation of the slope with time according to the ${}_Aa_1(t)$ *-curve.*

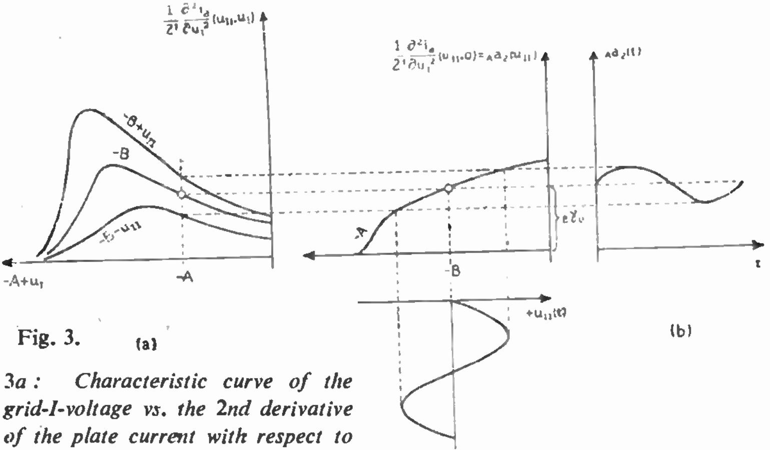


Fig. 3.

3a : Characteristic curve of the grid-I-voltage vs. the 2nd derivative of the plate current with respect to grid-I-voltage, taking grid-II-voltage as parameter.

3b : Variation with grid-II-voltage of the 2nd derivative of the plate current with respect to grid-I-voltage, applying to grid I the bias minus A. Varying grid-II-voltage sinusoidally produces a variation with time of that 2nd derivative according to the $_{A}a_2(t)$ *-curve.*

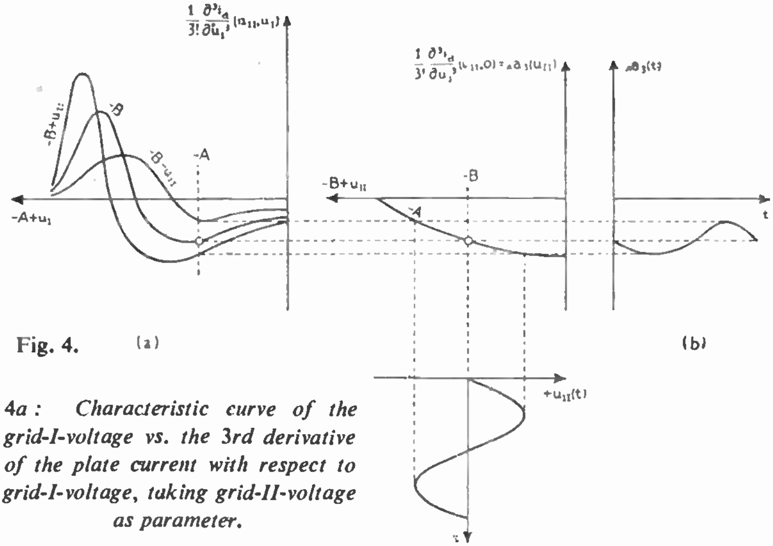


Fig. 4.

4a : Characteristic curve of the grid-I-voltage vs. the 3rd derivative of the plate current with respect to grid-I-voltage, taking grid-II-voltage as parameter.

4b : Variation with grid-II-voltage of the 3rd derivative of the plate current with respect to grid-I-voltage, applying to grid I the bias minus A. Varying grid-II-voltage sinusoidally produces a variation with time of that 3rd derivative according to the $_{A}a_3(t)$ *-curve.*

the term " grid " will be used when referring to control grids.) In other words the same kind of curve system will be obtained whether grid I or whether grid II is being given the parametric values.

In figure 1a such a system of curves is shown. By applying the negative biases minus A and minus B to the grids I and II respectively, the operating point O is fixed in the diagram. The change of current occurs along the curve with the parameter minus B if grid II, say, is kept at a constant potential minus B and grid I is made more positive. If now grid I is kept at its constant potential minus A and grid II is made more positive the change of current will be in the same direction as in the previous case, viz. the current will increase. This can be verified on the diagram by observing the different parameter values of the grid II voltage u_{II}. The change of current will now occur along the vertical line through $u_I = -A$ in figure 1a. Incidentally this also demonstrates that both control grids have basically the same influence upon the flow of electrons in the mixing tube. (See Fig. 5.)

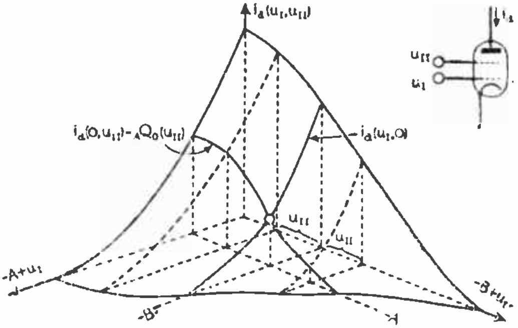


Fig. 5.—Three dimensional characteristic of a double control grid tube, *co-ordinating to each arbitrary set of control voltages* u_I *and* u_{II} *a unique value of plate current* i_a.

If the tube is now used in the usual manner, that is to say, if an intermediate frequency ω_{IF} is to be produced from a signal frequency ω and a local oscillator frequency Ω, one grid then carries the signal and the other carries the local frequency. The simultaneous application of control voltages on both grids will find its expression in the diagram by a complicated shifting of the momentary point of operation in the u_I/i_a plane. If the two frequencies impressed are commensurable, tracks of this point shaped like Lissajous-figures are described. But in the particular case of IF generation these tracks would become very intricate in their structure, especially if the signal is a modulated carrier. Actually no practical conclusions could be drawn from such diagrams.

A mathematical consideration, however, yields the desired results, namely the predetermination of all possible frequencies with their corresponding amplitudes appearing in the plate current.

Assume the signal voltage u_I impressed upon grid I, and grid II for a moment kept at a constant potential say minus B. As already stated before, the curve with the parameter minus B in figure 1a then gives full information about the relation between grid 1 and the plate current. It is convenient to develop this function into a Taylor series for the operating point O, i.e.,

$$(1) \ldots\ldots\ldots i_a = {}_Aa_0 + {}_Aa_1u_I + {}_Aa_2 . u_I^2 + {}_Aa_3u_I^3 + \ldots = \sum_{\mu=0}^{\infty} {}_Aa_\mu u_I^\mu$$

The index A indicates the dependence of the coefficient upon the bias A.

If the signal is a pure sinoid,

$$u_I = U_I \sin \omega t$$

the plate current is given by

$$(2)\ldots\ldots\ldots i_a = \sum_{\mu=0}^{\infty} {}_Aa_\mu U_I^\mu (\sin \omega t)^\mu$$

Noting the trigonometric relations :

$$(2a).\begin{cases} \sin^2\theta = m_{20} - m_{22}\cos 2\theta & = \frac{1}{2}(1 - \cos 2\theta) \\ \sin^3\theta = m_{31}\sin\theta - m_{33}\sin 3\theta & = \frac{1}{4}(3\sin\theta - \sin 3\theta) \\ \sin^4\theta = m_{40} - m_{42}\cos 2\theta + m_{44}\cos 4\theta & = \frac{1}{8}(3 - 4\cos 2\theta + \cos 4\theta) \\ \sin^5\theta = m_{51}\sin\theta - m_{53}\sin 3\theta - m_{55}\sin 5\theta & = \frac{1}{16}(10\sin\theta - 5\sin 3\theta - \sin 5\theta) \end{cases}$$

Re-arranging equation (2) after substituting these relations gives

$$(3)\ldots\ldots\ldots i_a = \sum_{\mu=0}^{\infty} {}_Aa_\mu^* \begin{matrix}\sin\\ \cos\end{matrix}(\mu\omega t) \qquad \text{See Fig. 6.}$$

It is understood that in formula (3) cos is to be taken for even values of μ including $\mu=0$, and sin for odd values of μ. The coefficients ${}_Aa_\mu^*$ are then given by :

$$(4)\quad \begin{array}{l|l} {}_Aa_0^* = {}_Aa_0 + {}_Aa_2\frac{1}{2}U_I^2 + {}_Aa_4\frac{3}{8}U_I^4 + \ldots & {}_Aa_2^* = {}_Aa_2\frac{1}{2}U_I^2 + {}_Aa_4\frac{4}{8}U_I^4 + \ldots \\ {}_Aa_1^* = {}_Aa_1U_I + {}_Aa_3\frac{3}{4}U_I^3 + {}_Aa_5\frac{10}{16}U_I^5 + . & {}_Aa_3^* = -{}_Aa_3\frac{1}{4}U_I^3 - {}_Aa_5\frac{5}{16}U_I^5 + . \end{array}$$

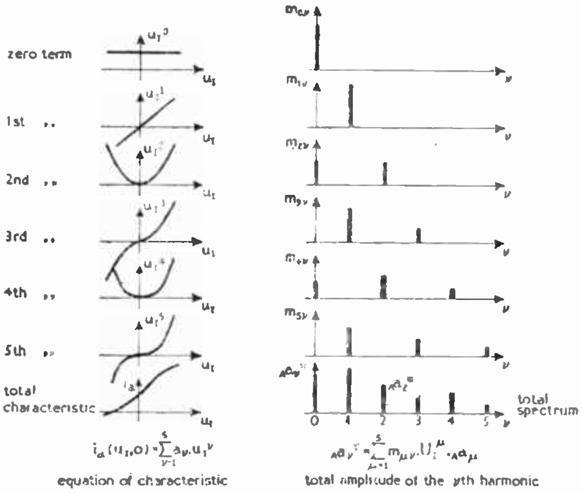


Fig. 6.—The effect of a sinoidal voltage u_1 impressed on a single characteristic, *e.g.*, $i_a(u_I, o)$ (*see Fig.* 5) *is demonstrated by showing the frequency spectra separately for each term of the Taylor series representing* $i_a(u_I, o)$, *i.e. showing the frequency spectra corresponding to the trigonometric formulae* (2*a*). *Summing up, the Taylor terms on the left side gives the original characteristic, and summing up the frequency spectra on the right side of the Fig. results in the total frequ. spectrum given by formula* (3).

Equation (3) shows that the output of the tube (the current) contains the fundamental of the signal ω and all its harmonics, the amplitudes of which fall off the more rapidly the smaller the amount of curvature of the characteristic at the operating point O, and the smaller the signal amplitude U_I.

Suppose grid II is given a small increment of voltage $\triangle u_{II}$ so that the total grid II voltage amounts to $(-B + \triangle u_{II})$, a new curve results (see figure 1a) i.e. signal is now "projected" upon this curve, and the resulting current components are obtained by applying the process just described, the difference being only that new coefficients for the Taylor expansion around the new working point O_1 have to be found. Calling the new coefficient ${}_A b_\mu$ the equation for the current then reads :

$$(5) \ldots\ldots\ldots i_a = \sum_{\mu=0}^{\infty} {}_A b_\mu U_I^\mu (\sin \omega t)^\mu = \sum_{\mu=0}^{\infty} {}_A b_\mu^* \frac{\sin}{\cos}\left(\mu\omega t\right) =$$

$$i_a = {}_A b_0^* + {}_A b_1^* \sin \omega t + {}_A b_2^* \cos 2\omega t + {}_A b_3^* \sin 3\omega t + \ldots$$

It will be seen that equations (2) and (5) are essentially the same, the difference consisting in the coefficients a and b. These coefficients differ only because grid II voltage was changed. Consequently they are functions of this second control voltage u_{II}. With this conception in mind equation (1) can be written more generally as :

$$(6) \ldots\ldots\ldots i_a (u_{II}\ u_I) = \sum_{\mu=0}^{\infty} {}_A a_\mu(u_{II}) \,.\, u_I{}^\mu$$

$$(6a) \ldots\ldots\ldots {}_A a_0 (u_{II}) = i_a (u_{II}, o)$$

$${}_A a_1 (u_{II}) = \frac{1}{1!} \frac{\partial i_a}{\partial u_I} (u_{II}, o)$$

$${}_A a_2 (u_{II}) = \frac{1}{2!} \frac{\partial^2 i_a}{\partial u_I{}^2} (u_{II}, o)$$

$${}_A a_3 (u_{II}) = \frac{1}{3!} \frac{\partial^3 i_a}{\partial u_I{}^3} (u_{II}, o)$$

For examination of this result first consider the zero order coefficient ${}_A a_0(u_{II})$ of the Taylor expansion. ${}_A a_0(u_{II})$ means that the DC component of the current for the grid I bias minus A is a function of u_{II} as shown in Fig. 1b. If u_{II} equals zero, the zero order coefficient becomes

$${}_A a_0(o) = {}_B \alpha_0$$

Index B indicates the dependence of this value on the grid II bias minus B. If now u_{II} is applied, ${}_A a_0$ changes its value accordingly. For small increments $\triangle u_{II}$ the increase or decrease of ${}_A a_0(u_{II})$ may be expressed by adding a linear term to the quiescent value ${}_B \alpha_0$, so that

$$(7) \ldots\ldots\ldots {}_A a_0 (\triangle u_{II}) = {}_B \alpha_0 + {}_B \alpha_1 \,.\, \triangle u_{II}$$

Relation (7) will in general hold good for small increments of u_{II} only. For larger values of u_{II} apparently new correction terms have to be added to equation (7). In consequence a power series for ${}_A a_0(u_{II})$ is obtained.

$${}_A a_0(u_{II}) = {}_B \alpha_0 + {}_B \alpha_1 u_{II} + {}_B \alpha_2 u_{II}{}^2 + {}_B \alpha_3 u_{II}{}^3 + \ldots.$$

$$(8) \ldots\ldots\ldots {}_A a_0(u_{II}) = \sum_{\nu=0}^{\infty} \alpha_\nu u_{II}{}^\nu = i_a(u_{II}, o)$$

This dependence of ${}_Aa_0$ on u_{II} is demonstrated by Fig. 1b which is constructed from figure 1a by plotting parameters u_{II} on the abscissa in Fig. 1b against the corresponding current values. The new curve has minus A as parameter and its Taylor expansion for the point O is equation (8).

As to the first order coefficient ${}_Aa_1(u_{II})$ of equation (6) similar arguments can be put forward. ${}_Aa_1(u_{II})$ is the slope of the curve in figure 1a for the grid I—bias minus A and is a function of u_{II}. For the sake of completeness the total slope curves $\frac{\partial i_a}{\partial u_I}\left(u_{II}, u_I\right)$ against u_I are plotted in Fig. 2a. Then the values of ${}_Aa_1(u_{II})$ appear as ordinates of the bias minus A for different parameters u_{II}, and a curve can again be plotted in Fig. 2b, viz. ${}_Aa_1(u_{II})$ against u_{II} with minus A as parameter. This curve, developed into a Taylor series, gives

$${}_Aa_1(u_{II}) = {}_B\beta_0 + {}_B\beta_1 u_{II} + {}_A\beta_2 u_{II}^2 + {}_B\beta_3 u_{II}^3 + \dots .$$

$$(9)\dots\dots\dots {}_Aa_1(u_{II}) = \sum_{\nu=0}^{\infty} {}_B\beta_\nu u_{II}^\nu = \frac{1}{1!}\frac{\partial i_a}{\partial u_I}(u_{II}, o)$$

Similar relations are obtained for all other coefficients of equation (6) and are shown graphically in the Figs. 3b and 4b.

$$(10)\dots\dots\dots {}_Aa_2(u_{II}) = \sum_{\nu=0}^{\infty} {}_B\gamma_\nu u_{II}^\nu = \frac{1}{2!}\frac{\partial^2 i_a}{\partial u_I^2}(u_{II}, o). \quad \text{Fig. 3b.}$$

$$(11)\dots\dots\dots {}_Aa_3(u_{II}) = \sum_{\nu=0}^{\infty} {}_B\delta_\nu u_{II}^\nu = \frac{1}{3!}\frac{\partial^3 i_a}{\partial u_I^3}(u_{II}, o). \quad \text{Fig. 4b.}$$

Therefore equation (6) can be written

$$(12)\dots\dots i_a(u_I, u_{II}) = \sum_{\nu=0}^{\infty} {}_B\alpha_\nu . u_{II}^\nu . u_I^0 + \sum_{\nu=0}^{\infty} {}_B\beta_\nu u_{II}^\nu . u_I^1 + \sum_{\nu=0}^{\infty} {}_B\gamma_\nu u_{II}^\nu . u_I^2$$

$$+ \sum_{\nu=0}^{\infty} {}_B\delta_\nu u_{II}^\nu . u_I^3 + \dots .$$

Expression (12) gives full information about everything that may occur in the output of the tube if the input voltages u_I and u_{II} are given. Of course, an analogous expression could have been obtained, had the original characteristic been plotted with u_{II} as obscissa and u_I as parameter. The coefficients α, β, etc. would then be different from those in equation (12)—although the tube remained the same.

3. APPLICATIONS OF THE GENERAL FORMULA (12).

A. The Double Control Grid Tube as Frequency Convertor.

a. *IF generation and its distortion.*

It is now easy to interpret the last expression if definite input voltages are assumed. First of all the generation of an intermediate frequency shall be investigated. As already suggested above, let grid I carry the signal voltage u_I :

$$(13)\dots\dots\dots u_I = U_I\,(1 + m \sin pt) \sin \omega t$$

which is the carrier ω modulated by the audio frequency p, and let grid II carry the local oscillator frequency Ω :

$$14)\dots\dots\dots u_{II} = U_{II} \sin \Omega t$$

In order to be able to work out formula (12) in a systematic manner, it will be advisable to substitute (13) and (14) in the individual terms first, thus obtaining frequency spectra, i.e. polynomials which are then tabulated. The final result is obtained by carrying out the multiplications.

To start with the $\sum$ terms it is seen that the substitution of the pure sinoid u_{II} leads to a sum of frequencies $\Omega, 2\Omega, 3\Omega$ .., an expression which is similar to that in formula (5).

The spectra of u_I^μ must be worked out individually since u_I consists of a number of frequencies. No simple formula exists giving an immediate result since the combination frequencies which occur must be calculated for each given value of μ separately. For a purely qualitative result it suffices to use the formula

$$15)\ldots\ldots\ldots 2\pi f = h_1\omega_1 \pm h_2\omega_2 \pm h_3\omega_3 \pm \ldots\ldots \pm h_n\omega_n$$

$$(15a)\ldots\ldots \sum_{\kappa=1}^{n} h_\kappa = \mu \quad , \quad h_\kappa = 0, 1, 2, 3, \ldots.\mu$$

where $\omega_1, \ldots \omega_n$ are the n frequencies impressed upon grid I and $2\pi f$ are the combination frequencies generated due to the μ^{th} order of the characteristic. For the signal given by (13) the combination frequencies are

$$(16)\ldots\ldots\ldots 2\pi f = h_1\omega \pm h_2(\omega + \rho) \pm h_3(\omega - \rho)$$

$$(16a)\ldots\ldots \sum_{\kappa=1}^{3} h^\kappa = \mu$$

If it is desired also to calculate the amplitudes of the combination frequencies, a more complicated formula must be used, the execution of which, though being rather laborious, yields the desired results in a very systematic manner, thus excluding mistakes to a large extent. If

$$(17)\ldots\ldots\ldots u = \sum_{\kappa=1}^{n} U_\kappa \sin \omega_\kappa t \quad \text{then}$$

$$(18)\ldots\ldots u^\mu = -\frac{1}{2^{\mu-1}} \sum_{\kappa_1=1,\,\kappa_2=1,\ldots\kappa_\mu=1}^{n} U_{\kappa_1} U_{\kappa_2} \ldots U_{\kappa_\mu} \begin{matrix}\sin\\ \cos\end{matrix} \left(\omega_{\kappa_1} \pm \omega_{\kappa_2} \pm \ldots \omega_{\kappa_\mu}\right) t$$

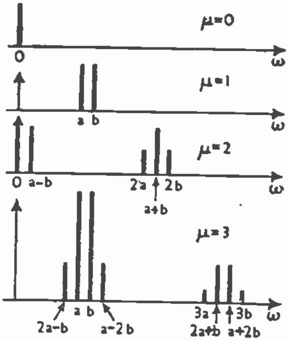


Fig. 7.—Illustration of Formula (18) *for* n=2, μ=0, 1, 2, 3.
Frequency spectra due to the impression of two sinoidal oscillations of frequencies a *and* b *upon a single characteristic* $i_a(u_1, o)$ *consisting of terms up to the third order.*

then the rule being :—

(1) take sin for odd and cos for even μ.

(2) Go through all possible combinations for $\kappa_1, \kappa_2, \ldots \kappa_\mu$

(3) For a given set of chosen $\kappa_1, .. \kappa_\mu$ go through all possible combinations of plus or minus signs inside the bracket. One change of sign in the bracket means a change of sign of the whole expression, therefore two changes of sign inside the bracket leave the sign of the whole expression unaltered etc. See Fig. 7.

Of course, also direct the way of calculation can be chosen by working out

$$(19) \ldots\ldots\ldots u^{\mu} = \left[\sum_{\kappa=1}^{n} U_{\kappa} \sin \omega^{\kappa} t \right]^{\mu} = U_1^{\mu} \sin^{\mu} \omega_1 t + \ldots$$

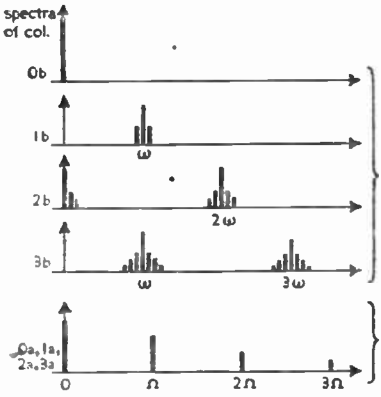
but this method is not very convenient, since trigonometric transformations must constantly be applied and computations in a tabulated form cannot be carried out so easily as in the previous scheme. After all, formula (18) has been derived from (19), and the former, in its more advanced form, is bound to offer advantages for the computation.

Referring again to formula (12) which is to be interpreted, it can, by substituting (14) and applying relations similar to (5), be rewritten as follows :

$$(20) \ldots i_a(u_I, u_{II}) = \left[\sum_{\nu=0}^{\infty} {}_B\alpha_\nu^* \begin{matrix}\sin\\ \cos\end{matrix} \left(\nu\Omega t\right) \right] . u_I^0 + \left[\sum_{\nu=0}^{\infty} {}_B\beta_\nu^* \begin{matrix}\sin\\ \cos\end{matrix} \left(\nu\Omega t\right) \right] . u_I^1 +$$

$$+ \left[\sum_{\nu=0}^{\infty} {}_B\gamma_\nu^* \begin{matrix}\sin\\ \cos\end{matrix} \left(\nu\Omega t\right) \right] . u_I^2 + \left[\sum_{\nu=0}^{\infty} {}_B\delta_\nu^* \begin{matrix}\sin\\ \cos\end{matrix} \left(\nu\Omega t\right) \right] . u_I^3 + \ldots$$

The spectra of u_I^{μ}, if u_I follows equation (13), have been calculated by means of method (18) and are computed in columns 0b, 1b, 2b, 3b, together with the spectra of the $\sum$ terms in columns 0a, 1a, 2a, 3a, of the following table I. See Fig. 8.



Spectra arising from the signal (pure tone-modulated carrier) impressed on grid I due to the characteristic $i_a(u_I, o)$, *if* u_{II} *is kept zero and constant.*

Spectra arising from the local oscillator frequency impressed on grid II due to the characteristic $i_a(o, u_{II})$, *if* u_I *is kept zero and constant.*

Fig. 8.—Graph of the frequency spectra appearing in Table I.

Table I†

Term of equation (20)															
0				1				2				3			
$\sum$		u_I^0		$\sum$		u_I^1		$\sum$		u_I^2		$\sum$		u_I^3	
0a		0b		1a		1b		2a		2b		3a		3b	
A	fr	A	fr	A	fr	A	fr	A	fr	A	fr	A	fr	A	fr
$_B\alpha_0^*$	0	1	0	$_B\beta_0^*$	0	U_I	ω	$_B\gamma_0^*$	0	$-\frac{1}{2}U_I^2\left(1+\frac{m^2}{2}\right)$	2ω	$_B\delta_0^*$	0	$\frac{3}{4}U_I^3\left(1+\frac{3}{2}m^2\right)$	ω
$_B\alpha_1^*$	Ω			$_B\beta_1^*$	Ω	$\frac{m}{2}U_I$	$\omega\pm\rho$	$_B\gamma_1^*$	Ω	$-\frac{1}{2}U_I^2 m$	$2\omega\pm\rho$	$_B\delta_1^*$	Ω	$\frac{9}{8}U_I^3 m\left(1+\frac{m^2}{4}\right)$	$\omega\pm\rho$
$_B\alpha_2^*$	2Ω			$_B\beta_2^*$	2Ω			$_B\gamma_2^*$	2Ω	$-\frac{1}{2}U_I^2\frac{m^2}{4}$	$2\omega\pm 2\rho$	$_B\delta_2^*$	2Ω	$\frac{9}{16}U_I^3 m^2$	$\omega\pm 2\rho$
$_B\alpha_3^*$	3Ω			$_B\beta_3^*$	3Ω			$_B\gamma_3^*$	3Ω	$+U_I^2 m$	ρ	$_B\delta_3^*$	3Ω	$\frac{3}{32}U_I^3 m^3$	$\omega\pm 3\rho$
										$U_I^2\frac{m^2}{4}$	2ρ			$-\frac{1}{4}U_I^3\left(1+\frac{3}{2}m^2\right)$	3ω
														$-\frac{3}{8}U_I^3 m\left(1+\frac{m^2}{4}\right)$	$3\omega\pm\rho$
														$-\frac{3}{16}U_I^3 m^2$	$3\omega\pm 2\rho$
														$-\frac{1}{32}U_I^3 m^3$	$3\omega\pm 3\rho$

---

† All coefficients marked with asterisks (*) go conformly with formula (3).

In order now to obtain the final results the multiplications proper have to be carried out. They are multiplications of two polynomials, i.e. spectra, each consisting of a sum of terms, one term being an amplitude times cos or sin of some frequency. The amplitudes and the corresponding frequencies of these polynomials are found in the columns of the table marked 1a, 1b, 2a, 2b, etc. From the trigonometric relations

$$\left.\begin{aligned} \sin\alpha\cos\beta &= \tfrac{1}{2}\sin(\alpha+\beta) + \tfrac{1}{2}\sin(\alpha-\beta) \\ \sin\alpha\sin\beta &= \tfrac{1}{2}\cos(\alpha-\beta) - \tfrac{1}{2}\cos(\alpha+\beta) \\ \cos\alpha\cos\beta &= \tfrac{1}{2}\cos(\alpha+\beta) + \tfrac{1}{2}\cos(\alpha-\beta) \end{aligned}\right\} \quad \text{See Fig. 9} \qquad (21)$$

it will be seen that each product of two frequencies results in the sum of sum and difference frequencies. It also follows that the amplitudes of the sum or difference frequency equal one-half of the product of the componental amplitudes.

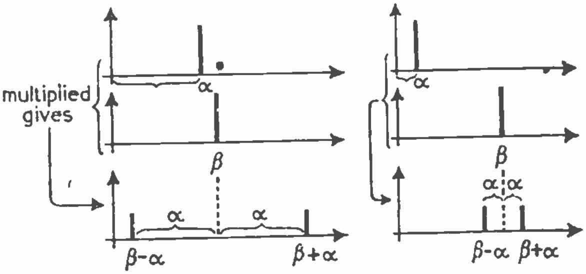


Fig. 9. — The multiplication of two frequency spectra α and β results in sum and difference frequency. *This operation is mathematically expressed by formula* (21), *and is the very essence of the problem of modulation, viz. the generation of sidebands. If the spectrum* α *is impressed upon one grid, and similarly* β *on the other grid of the mixer, such a multiplication occurs only by virtue of the mixed derivatives* $\partial^{\mu+\nu} i_a / \partial u_I^{\mu} \partial u_{II}^{\nu}$ *of the characteristic surface. The lowest and most effective of these mixed derivatives is that of the second order, viz.,* $\partial^2 i_a / \partial u_I \, \partial u_{II}$, *which measures the change of slope* (*see Fig.* 11*b*).

Since it is not intended, in view of practical considerations, to write down the total expression for the current, the terms in equation (20) and their significance will be discussed individually with the aid of Table I and Fig. 10.

Zero term of equation (20) :

$u_I{}^0 = 1$, consequently the first term consists of a DC component of magnitude ${}_B\alpha_0{}^*$, of the oscillator frequency Ω and its harmonics ($\nu\Omega$) the amplitudes of which are given by the coefficients ${}_B\alpha_I{}^*$, ${}_B\alpha_2{}^*$, . . . etc.

First term of equation (20) :

The spectrum is found by forming sum and differences of all terms appearing in the columns 1a and 1b. Take, for instance, the zero term of column 1a which means frequency zero, i.e. DC, amplitude ${}_B\beta_0{}^*$, form sum and difference of this zero frequency and all frequencies of column 1b whence ω, $\omega \pm \rho$ is obtained. In other words, the original modulated carrier ω impressed on grid 1 appears also in the current with the amplitude ${}_B\beta_0{}^* U_1$. Next take the first term of 1a, i.e. frequency Ω with amplitude ${}_B\beta_1{}^*$, and combine with column 1b. Result :

$$\Omega \pm \omega, \Omega \pm \omega \pm \rho \quad \ldots \quad \text{See Fig. 11.} \qquad (22)$$

This is the upper and the lower IF modulated without distortion by ρ. Since these frequencies are the only ones desired—for it is the very purpose of a mixing tube to generate them—it will be worth while to discuss this point in more detail.

It follows from the foregoing that the amplitude of the lower IF carrier say, is one-half of the product of the componental amplitudes U_1 and ${}_B\beta_1^*$ hence :

(23) . . . . $A(\Omega - \omega) = I_{IF}' = \frac{1}{2}\,{}_B\beta^*_1 U_1$ [1]

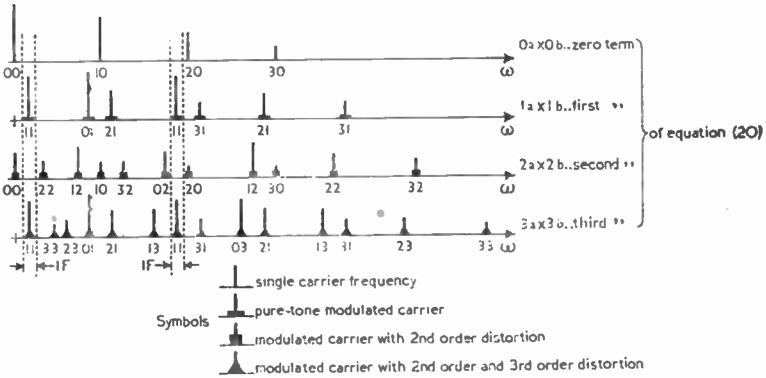


Fig. 10.—The complete frequency spectra appearing in the output of the double control grid tube *if a pure-tone modulated carrier is impressed on the signal grid, and a local oscillation on the other grid, and if all terms higher than third are neglected. It can be seen from the diagram that the filtered IF (both the lower and the higher) suffer 2nd and 3rd harmonic modulation distortion due only to the third term of equation (20). It can be stated quite generally for mixers as well as for HF amplifying tubes that modulation distortion is merely due to the higher uneven order terms of the characteristic.*

Explanation of the figures : e.g., 13 in the 3rd order spectrum means the two combination frequencies resulting from the fundamental (1st) oscillator frequency (col. 3a) and the 3rd harmonic band (3ω) of the signal (col. 3b). (See Fig. 8.)

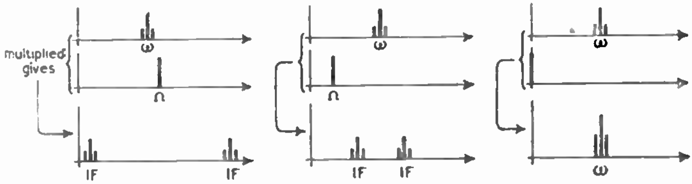


Fig. 11.—Frequency changing is principally a modulation process. *One of the side bands arising—usually the lower—is being used as IF. If the oscillator frequency is decreased, and eventually made zero, the frequency changer has turned into an ordinary amplifying tube. The Fig 11 also demonstrates why the conversion transconductance is one-half of β_1^**

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[1] $A(\Omega - \omega) = I_{IF}$ is to denote : the amplitude of the oscillation of frequency $(\Omega - \omega)$ is equal to I_{IF}

It becomes evident from equation (23) that $\frac{{}_{B}\beta_1^*}{2}$ must be the conversion transconductance, viz., the factor connecting IF output current with the HF input voltage. Therefore :

(24) . . . . . $g_c = \frac{1}{2}\, {}_{B}\beta_1^*$

By referring to equations (4) and (9) it will be clear how (25) is obtained.

(25) . . . . . ${}_{B}\beta_1^* = {}_{B}\beta_1 U_{II} + {}_{B}\beta_3 \frac{3}{4} U_{II}^3 - {}_{B}\beta_5 \frac{10}{16} U_{II}^5 + \ldots\ldots$

Examining this in more detail it may be stated that the β's are the coefficients of the Taylor expansion for the slope of the signal-voltage-to-plate-current characteristic as a function of the local oscillator voltage u_{II}. This function is shown in figure 2b. If the sinoid $U_{II} \sin \Omega t$ is " projected " upon this curve a non-sinusoidal trend of slope variation is the result. There are now two ways of finding the fundamental of this non-sinusoidal slope variation. The first has already been indicated above : develop the function into a Taylor series, impress $U_{II} \sin \Omega t$, collect all terms containing Ω, the sum of which will then be the amplitude ${}_{B}\beta_1^*$. The second way makes use of the Fourier analysis. If g(t) denotes the non-sinusoidal slope variation with time (see Fig. 2b), its fundamental and its harmonic components g_ν are given by the well-known formula for the Fourier coefficients :

(26) . . . . . $g_\nu = \frac{1}{\pi}\int_0^{2\pi} g(t) \sin (\nu \Omega t)\, d\,(\Omega t) = {}_{B}\beta_\nu^*$

The conversion transconductance g_c then is obtained for $\nu = 1$

(26a) . . . . . $g_c = \frac{1}{2} g_1 = \frac{1}{2} {}_{B}\beta_1^* = \frac{1}{2\pi}\int_0^{2\pi} g(t) \sin \Omega t\, d\,(\Omega t)$

As to the sidebands it is found that the amplitude of one IF side frequency is given by $\frac{m}{2} U_I g_c$ so that the ratio between carrier and sideband for the IF and HF has remained unaltered. It is clear that this must be so, since both HF carrier and HF sideband have been transformed into IF carrier and IF sideband by exactly the same process. Therefore the depth of modulation of the signal and of the IF are identically the same—as long as no distortion occurs.

It seems opportune here to insert a remark on the possibilities of simplifying and idealising the characteristic of a double control grid tube suitable for a mixing process. Fig. 5 has already demonstrated that a three dimensional surface is needed to characterise a double control grid tube, similarly as a single two dimensional line is sufficient for characterising a single control grid tube. In order really to produce an IF a conversion transconductance must exist. In other words ${}_{B}\beta_1^* \neq 0$ See equations (22 and 23).

Since ${}_{B}\beta_1^* = {}_{B}\beta_1 U_{II} + {}_{B}\beta_3 \frac{3}{4} U_{II}^3 + \ldots\ldots$ (25)

the above condition implies that at least ${}_{B}\beta_1$ must be unequal to zero even if all following terms of (25) are allowed to vanish for the sake of idealisation.

It can be seen in the appendix that ${}_{B}\beta_1 = \frac{\partial^2 i_a (o, o)}{\partial u_I\, \partial u_{II}}$

so that $\frac{\partial^2 i_a (o, o)}{\partial u_I\, \partial u_{II}} \neq 0$ can be taken as a criterion for the existence of a conversion transconductance.

This condition now cannot be fulfilled by a linear relation $i_a = i_a(u_I, u_{II})$ in other words, the characteristic surface of the mixer can never be a plane or linear surface if a mixing process is to be performed. (See Fig. 11b.) This only confirms the well-known law that a non-linear medium is always necessary if new combination and harmonic frequencies are to be generated from a given set of frequencies. So it can be summarised that the characteristic must be a curved line for a single control grid tube, and a curved surface for the double control grid tube in order to serve as a new-frequency-producing medium.

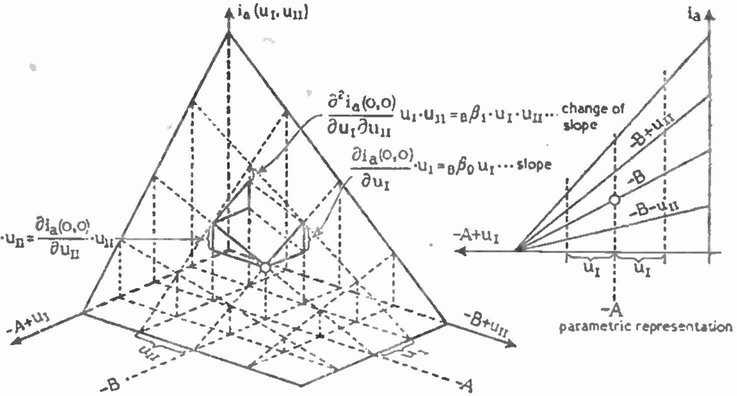


Fig. 11b.—The characteristic of a mixer must be a curved surface *if an IF is to be generated. The figure demonstrates the simplest possible surface fulfilling these requirements. It deviates from the plane merely by the mixed partial second order derivative* $\partial^2 i_a / \partial u_I \, \partial u_{II}$, *and would characterise a mixer which is ideal from the point of view of distortion, etc.*

If ${}_B\beta_0$ *is called the slope of the signal grid characteristic, then* ${}_B\beta_1 = \frac{\partial^2 i_a}{\partial u_I \, \partial u_{II}}$, *the second order mixed derivative represents the change of slope, due to the oscillator voltage, and only this change of slope is responsible for the mixing or intermodulation process.*

The fact that it is possible to construct a curved surface out of straight lines (see Fig. 11b) may be misleading at first glance, particularly if the parametric representation of Figs. 1 to 4 is used. The only consequence of such a curved surface composed of straight lines is that no rectification (DC generation) takes place contrary to the inevitable DC effect occurring in a single control grid tube suitable for IF generation.

Finally, if the 2nd, etc., and the νth term of column 1a is combined with column 1b higher undistorted IF's are produced, viz.:

$$(\nu\Omega \pm \omega), \; (\nu\Omega \pm \omega \pm \rho)$$

Second term of equation (20):

Taking the zero, 1st, 2nd, etc., νth term of column 2a and combining with column 2b:

$$(\nu\Omega \pm 2\omega), (\nu\Omega \pm 2\omega \pm \rho), (\nu\Omega \pm 2\omega \pm 2\rho), (\nu\Omega \pm \rho), (\nu\Omega \pm 2\rho)$$
$$\nu = 0, 1, 2, 3 \; . \; . \; . \; .$$

It must be borne in mind that the output of the tube is always fed to a bandpass filter which passes frequencies in the neighbourhood of ω_{IF} and suppresses the remainder of the spectrum. Since all the frequencies generated by the second and zero term of equation (20) lie beyond the range of the IF, they are all suppressed by the filter. The same applies to those frequencies produced by the first term of equation (20) $(\nu\Omega \pm \omega)$, $(\nu\Omega \pm \omega \pm \rho)$ for which ν may have the value of any positive integer with the exception of $\nu = 1$.

Third term of equation (20) :

Combining columns 3a and 3b the following frequencies are obtained :

Amplitude	Frequency	Section
$\frac{9}{16} m^2 U_I^3 {}_B\delta_\nu^*$	$\nu\Omega \pm \omega \pm 2\rho$	a
$\frac{3}{32} m^3 U_I^3 {}_B\delta_\nu^*$	$\nu\Omega \pm \omega \pm 3\rho$	
$\frac{3}{4} U_I^3 (1 + \frac{3}{2} m^2) {}_B\delta_\nu^*$	$\nu\Omega \pm \omega$	
$\frac{9}{8} U_I^3 m (1 + \frac{m^2}{4}) {}_B\delta_\nu^*$	$\nu\Omega \pm \omega \pm \rho$	
. . . . .	$(\nu\Omega \pm 3\omega)$, $(\nu\Omega \pm 3\omega \pm \rho)$	b
. . . . . .	$(\nu\Omega \pm 3\omega \pm 2\rho)$, $(\nu\Omega \pm 3\omega \pm 3\rho)$	

Section *b* is entirely uninteresting, as these frequencies will all be suppressed. The same applies to section *a* when $\nu = 0, 2, 3 \ldots$ (i.e., excluding $\nu = 1$). For $\nu = 1$, however, IF distortion terms are found, viz., the distortion sidebands $(\Omega \pm \omega \pm 2\rho)$ and $(\Omega \pm \omega \pm 3\rho)$. In addition the terms $(\Omega \pm \omega)$ and $(\Omega \pm \omega \pm \rho)$ contribute to a relatively small extent to the undistorted IF terms (22).

The distortion factor can be calculated in the following way :

$$(27) \quad \ldots\ldots \quad k = \frac{\sqrt{A^2(\Omega \pm \omega \pm 2\rho) + A^2(\Omega \pm \omega \pm 3\rho)}}{A(\Omega \pm \omega \pm \rho)}$$

$$(28) \ldots \begin{cases} A\left(\Omega \pm \omega \pm \rho\right) = \frac{9}{8} m\, U_I^3 \left(1 + \frac{m^2}{4}\right) {}_B\delta_1^* + \frac{m}{2}\, {}_B\beta_1^* U_I \\ A\left(\Omega \pm \omega \pm 2\rho\right) = \frac{9}{16} m^2\, U_I^3\, {}_B\delta_1^* \\ A\left(\Omega \pm \omega \pm 3\rho\right) = \frac{3}{32} m^3\, U_I^3\, {}_B\delta_1^* \end{cases}$$

$$k = \frac{\frac{9}{16}\, m^2\, U_I^2\, {}_B\delta_1^* \sqrt{1 + \frac{m^2}{36}}}{\frac{m}{2}\, U_I \left[{}_B\beta_1^* + \frac{9}{4}\, U_I^2\, {}_B\delta_1^* \left(1 + \frac{m^2}{4}\right)\right]} = \frac{m \sqrt{1 + \frac{m^2}{36}}}{\frac{8\, {}_B\delta_1^*}{9\, {}_B\delta_1^*\, U_I^2} + 2\left(1 + \frac{m^2}{4}\right)}$$

(29) . . . . $k \approx \dfrac{m}{2 + \dfrac{8}{9}\dfrac{{}_B\beta_1^*}{{}_B\delta_1^*} \cdot \dfrac{1}{U_I^2}}$ . . . . See Fig. 12

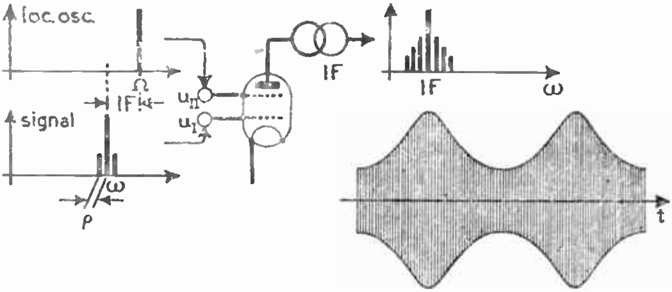


Fig. 12.—The oscillogram of the filtered " IF " shows modulation distortion when generated by a mixer having a cubic term in its characteristic. *The envelope also contains 2nd and 3rd harmonics of the fundamental modulation frequency p. If the cubic term is not present, i.e. if the signal grid characteristic consists of linear and square term, then only does the IF remain undistorted.*

The formula (29) shows that the distortion of the IF produced in the mixer increases with increasing ratio ${}_B\delta_1^*/{}_B\beta_1^*$, with larger signal amplitude U_I on grid 1 and also with higher degree of modulation. In (29) the terms containing m^2 have been neglected. This is permissible because in the numerator the error cannot exceed 1/72 (when $m = 1$), while the term $2 \cdot \frac{m^2}{4}$ is dimunitive in comparison with the sum total of the denominator (note that $\beta_1^*/\delta_1^* = 10^2 \ldots 10^3$). Summing up, it can be said that envelope distortion of an amplitude modulated IF may be caused by the mixing tube when

(30) . . . . ${}_B\delta_1^* \neq 0$

This value ${}_B\delta_1^*$ may be derived in a similar manner as (4b), thus

(31) . . . . ${}_B\delta_1^* = {}_B\delta_1\, U_{II} + {}_B\delta_3\, \frac{3}{4}\, U_{II}^3 + {}_B\delta_5\, \frac{10}{16}\, U_{II}^5 + \ldots.$

Undistorted IF generation would consequently imply

(30a) . . . . ${}_B\delta_1^* = 0$

remembering

(11) . . . . ${}_Aa_3\,(u_{II}) = {}_B\delta_0 + {}_B\delta_1 u_{II} + {}_B\delta_2 u_{II}^2 + {}_B\delta_3 u_{II}^3 + \ldots.$

it follows that

(32) . . . . ${}_B\delta_1 = {}_B\delta_3 = {}_B\delta_5 = \ldots = {}_B\delta_{2\nu+1} = 0,\ \nu = 0, 1, 2, 3$

This would mean that ${}_Ba_3\,(u_{II})$ is an even function with respect to the operating point, which in general will be unlikely. Observing figure 1a it is evident that making u_{II} more and more negative causes the curves to become flatter, and the curvature weaker. Therefore the values of the Taylor coefficients ${}_Aa_\nu\,(u_{II})$ will become smaller for $u_{II} < o$ and larger for $u_{II} > o$, which is demonstrated in figures 1b, 2b, 3b, 4b. This trend already excludes the possibility for an even function for ${}_Aa_3\,(u_{II})$ with respect to the operating point 0. It is therefore reasonable to conclude that (32) can, in a practical case, only be realised when also

(33) . . . $\quad {}_B\delta_2 = {}_B\delta_\nu = {}_B\delta_6 = \ldots = {}_B\delta_{2\nu+2} = o, \quad \nu = 0, 1, 2, 3 \ldots$

is satisfied simultaneously with (32). Consequently the condition for undistorted IF generation is

(34) . . . . $\quad a_3\,(u_{II}) = {}_B\delta_0 =$ constant and independent of u_{II}.

b. *IF cross modulation.*

The next item to be dealt with is the effect of cross modulation appearing in the IF. For the sake of completeness all relations referring to this effect will first be derived.

This effect has first been observed with HF amplifying tubes and it is best to commence with its analysis. If a desired unmodulated carrier ω_1 and an interfering carrier ω_2 modulated with ρ are brought together on the same grid of an amplifier tube the characteristic of which contains a third order term, the desired carrier ω_1 appears no longer unmodulated in the output but carries a small amount of modulation from the interfering carrier ω_2 (Fig. 13).

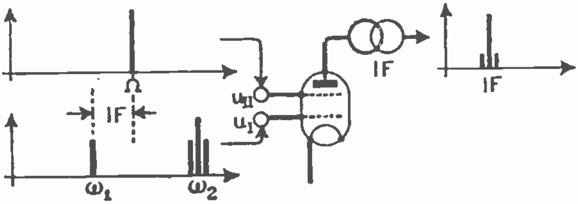


Fig. 13.—Crossmodulation as occurring in the frequency changer. *The desired and originally unmodulated signal ω_1, after conversion into the IF carries a small amount of modulation from a strong interfering a-m carrier ω_2. This can only occur when the characteristic contains a cubic and/or higher uneven order terms.*

If m_2 is the degree of modulation of the interfering carrier ω_2 and m_1 the unwanted degree of modulation of the desired carrier in the output, then the crosstalk factor is given by

(35) . . . . $\quad c_r = \dfrac{m_1}{m_2}$

In order to calculate c_r it would undoubtedly be the obvious way to work out the frequencies occurring in the output with the aid of formula (18) if (17) in this special case has the form

(35a) . . . . $\quad u = U_1 \sin \omega_1 t + U_2\,(1 + m_2 \sin \rho t) \sin \omega_2 t$

This method, however, is very laborious indeed ; and since the results are obtained automatically by consequent application of formula (18) it affords no opportunity for a proper understanding of this interesting problem. Another way is suggested.

Take an amplifier tube with a characteristic also containing a cubic term

(36) . . . . $i_a = a_0 + a_1 u + a_2 u^2 + a_3 u^3 = \sum_{\nu=0}^{3} a_\nu u^\nu$

if the desired carrier

(37 . . . . $u_1 = U_1 \sin \omega_1 t$

is impressed upon the grid, then

(38)..$i_a = \sum_{\nu=0}^{3} a_\nu^* \cdot \genfrac{}{}{0pt}{}{\sin}{\cos}\left(\nu\omega_1 t\right) = a_0^* + a_1^* \sin \omega_1 t + a_2^* \cos 2\omega_1 t + a_3^* \sin 3\omega_1 t$

represents the plate current, the a_ν^* being

(39) . . . . $a_0^* = a_0 + \frac{a_2}{2} U_1^2$

$$a_1^* = a_1 U_1 + \frac{3}{4} a_3 U_1^3$$

$$a_2^* = \frac{1}{2} a_2 U_1^2$$

$$a_3^* = -\frac{1}{4} a_3 U_1^3$$

The current i_1 of the fundamental is therefore :

$$i_1 = (a_1 U_1 + \frac{3}{4} a_3 U_1^3) \sin \omega_1 t$$

since $a_3/a_1 \approx 10^{-2} \ldots 10^{-3} \ll 1$ and U_1 is comparatively small

$$i_1 \approx a_1 U_1 \sin \omega_1 t$$

and the amplitude of the fundamental

(40) . . . . $I_1 \approx a_1 U_1 = g U_1$

is roughly proportional to the slope of the characteristic (36) in the working point, for

$$\left(\frac{di_a}{du}\right)_{u=0} = \left(a_1 + 2a_2 u + 3a_3 u^2\right)_{u=0} = a_1 = g$$

Since for the purpose of this analysis the characteristic is assumed to be precisely represented by a cubic equation, expression (36) holds good for any value of the voltage u. If now a shifting voltage u_2—which may be constant for the moment—is added to (37) the slope of (36) in this new working point will be given by

(41) . . . . $g = a_1 + 2a_2 u_2 + 3a_3 u_2^2$

Varying this shifting voltage sinusoidally, with a frequency ω_2

(41) becomes $g = a_1 + 2a_2 U_2 \sin \omega_2 t + 3a_3 U_2^2 \sin {}_2\omega_2 t$

(42) . . . . $g = \left[a_1 + \frac{3}{2} a_3 U_2^2\right] + 2a_2 U_2 \sin \omega_2 t + \frac{3}{2} a_3 U_2^2 \cos 2\omega_2 t$

In order to find the fundamental $I_1 = A(\omega_1)$ of the current in the presence of ω_2 equation (42) is multiplied by (37), and it will be seen that the fundamental is the result of the product between the constant term in brackets of (42) and equation (37). The other terms of (42), however, give combination frequencies $(\omega_2 \pm \omega_1)$, $(2\omega_2 + \omega_1)$ which lie far beyond the range of ω_1 if ω_2 is also a high frequency. Thus

$$(43) \quad \ldots \ldots I_1 = A(\omega_1) = \left[a_1 + \frac{3}{2} a_3 U_2^2\right] . U_1$$

i.e., I_1 depends not only upon U_1 but also upon the interfering carrier U_2. If U_2 is modulated, its modulation will also appear as a—though weaker—modulation of I_1. Putting

$u_2 = U_2 (1 + m_2 \sin \rho t)$ and substituting in (43)

$$I_1 = U_1\left[a_1 + \frac{3}{2} a_3 U_2^2 (1 + 2 m_2 \sin \rho t + m_2^2 \sin^2 \rho t)\right] =$$

$$= U_1\left[a_1 + \frac{3}{2} a_3 U_2^2 + \frac{3}{4} a_3 m_2^2 U_2^2\right] + \frac{3}{2} a_3 U_2^2 U_1 2m_2 \sin \rho t$$
$$- \frac{3}{4} a_3 U_2^2 U_1 m_2^2 \cos 2\rho t$$

neglecting the two terms in the bracket containing a_3

$$I_1 = U_1 a_1\left[1 + \left(3 \frac{a_3}{a_1} U_2^2 m_2\right) \sin \rho t - \left(\frac{3}{4} \frac{a_3}{a_1} U_2^2 m_2^2\right) \cos 2\rho t\right]$$

$$(44) \ldots . I_1 = U_1 a_1 [1 + {}_\rho m_1 \sin \rho t - {}_{2\rho} m_1 \cos 2\rho t]$$

Equation (44) proves that the desired carrier ω_1 is modulated by the modulation frequency ρ of the undesired carrier ω_2. Furthermore, the equation shows that this cross-modulation does not occur without distortion, and a second harmonic of the signal modulation frequency now appears in the cross-modulation. Since

$${}_\rho m_1 = 3 \frac{a_3}{a_1} U_2^2 m_2$$

the crosstalk factor is

$$(45) \quad \ldots . \quad c_r = \frac{{}_\rho m_1}{m_2} = 3 \frac{a_3}{a_1} U_2^2$$

and the audio distortion is given by

$$(46) \quad \ldots . \quad \frac{{}_{2\rho} m_1}{{}_\rho m_1} = \frac{m_2}{4}$$

The most important fact which is to be stressed once more is the relation of crosstalk with the cubic term $a_3 u^3$. If the cubic term vanishes no cross-modulation can occur. The amplitude of the new sidebands around ω_1 constituting this effect will, therefore, be proportional to a_3. From (44):

$$i_1 = a_1 U_1 [1 + {}_\rho m_1 \sin \rho t - {}_{2\rho} m_1 \cos 2\rho t] \sin \omega_1 t =$$

$$= a_1 U_1 \sin \omega_1 t + \frac{1}{2} U_1 . {}_\rho m_1 \cos (\omega_1 - \rho) t - \frac{1}{2} U_1 . {}_\rho m_1 \cos (\omega_1 + \rho) t$$
$$+ a_1 U_1 . {}_{2\rho} m_1 \cos 2 \rho t \sin \omega_1 t$$

is obtained, and

$$(47) \quad . \quad . \quad . \quad . \quad A\,(\omega_1 \pm \rho) = \frac{1}{2}\,a_1\,U_1\,.\,{}_{\rho}m_1 = \frac{3}{2}\,m_2\,U_1\,U^2_2\,.\,a_3$$

Referring again to the problem put forth at the beginning of this paragraph, viz., the investigation of cross-modulation in mixing tubes, a voltage $u_i = U_1 \sin \omega_1 t + U_2\,(1 + m_2 \sin \rho t) \sin \omega_2 t$ similar to (35a) must be applied to grid 1 for studying these effects. The third term of equation (20) then consists of the $\sum$ term and u_i^3. It has just been shown that the cubic term alone is responsible for the cross-modulation sidebands $(\omega_1 \pm \rho)$. Hence the elaboration of u_i^3 alone will, amongst others, contain the frequency $(\omega_1 \pm \rho)$ with its amplitude $\frac{3}{2}\,m_2\,U_1\,U_2^2$ as can be seen from (47).

Therefore a new table for the combination frequencies can be worked out. It is shown below, and only those frequencies that matter are inserted.

Term of equation (20)															
0				1				2				3			
$\sum$		u_i^0		$\sum$		u_i^1		$\sum$		u_i^2		$\sum$		u_i^3	
0a		0b		1a		1b		2a		2b		3a		3b	
A	fr	A	fr	A	fr	A	fr	A	fr	A	fr	A	fr	A	fr
α_0^*	0	1	0	β_0^*	0	U_1	ω_1	⋮	⋮	⋮	⋮	δ_0^*	0	⋮	⋮
α_1^*	Ω			β_1^*	Ω	U_2	ω_2	⋮	⋮	⋮	⋮	δ_1^*	Ω	$\frac{3}{2}m_2\,U_1\,U^2_2$	$\omega_1 \pm \rho$
⋮	⋮			⋮	⋮	$\frac{m_2}{2}U_2$	$\omega_2 \pm \rho$					δ_2^*	2Ω	$\frac{3}{8}m_2^2\,U_1\,U_2^2$	$\omega_1 \pm 2\rho$
⋮	⋮			⋮	⋮							⋮	⋮	⋮	⋮

Proceeding according to the rules laid down by formula (20) the following frequencies and their respective amplitudes are of interest :

$$A\,(\Omega \pm \omega_1) = \frac{1}{2}\,\beta_1{}^*\,U_1$$

$$A\,(\Omega \pm \omega_1 \pm \rho) = \frac{1}{2}\,\delta_1{}^*\,\frac{3}{2}\,m_2\,U_1\,U_2{}^2$$

$$A\,(\Omega \pm \omega_1 \pm 2\rho) = \frac{1}{2}\,\delta_1{}^*\,\frac{3}{8}\,m_2{}^2\,U_1\,U_2{}^2$$

therefore $$\frac{m_1}{2} = \frac{A\,(\Omega \pm \omega_1 \pm \rho)}{A\,(\Omega \pm \omega_1)} = \frac{3}{2}\,\frac{\delta_1{}^*}{\beta_1{}^*}\,m_2\,U_2{}^2$$

$$(48) \quad . \quad . \quad . \quad . \quad c_r = \frac{m_1}{m_2} = 3\,\frac{\delta_1{}^*}{\beta_1{}^*}\,U_2{}^2$$

Comparing formulæ (48) and (45) a striking similarity is observed. $a_1 = g$, the transconductance of the stationary characteristic of the single control grid tube is replaced by $\beta_1{}^* = 2g_c$ twice the conversion transconductance of the convertor. And similarly a_3 is replaced by $\delta_1{}^*$.

But since $${}_B\delta_1^* = {}_B\delta_1 \, U_{II} + {}_B\delta_3 \frac{3}{4} U_{II}^3 + {}_B\delta_5 \, U_{II}^5 + \dots$$

which follows from (4), exactly the same considerations can be applied as for ${}_B\beta_1^*$ when (26a) was derived. ${}_B\delta_1^*$ is the fundamental of $a_3[u_{II}(t)]$ if $u_{II} = U_{II} \sin \Omega t$. Therefore

$$(49) \quad . \; . \; . \; . \quad {}_B\delta_1^* = \frac{1}{\pi} \int_0^{2\pi} a_3\,(t) \sin \Omega\; t \; d(\Omega\, t) \qquad \textit{See } \text{Fig. 4b.}$$

The whole problem may be reconsidered in order to establish the natural relationship between a frequency convertor and an ordinary amplifier. It has been shown that the relevant point regarding the generation of an intermediate frequency is the variation of the first order coefficient of the signal voltage-to-plate current characteristic, in other words, the variation of the slope with time g(t).

Recalling equation (6) :

$$i_a\,(u_I, u_{II}) = a_0\,(u_{II}) + a_1\,(u_{II}) \,.\, u_I + a_2\,(u_{II}) \,.\, u_I^2 + a_3\,(u_{II}) \,.\, u_I^3 + \; . \; . \; . \; ,$$

take the first order term

$$a_1\,(u_{II}) \,.\, u_I = a_1\,[u_{II}\,(t)] \,.\, u_i = g(t) \,.\, u_I$$

This variation with time g(t) which in the analysis was represented by a power series need not necessarily be sinusoidal. On the contrary, it can be proved that the conversion transconductance may increase when departing from a sinusoidal slope change, and, in fact, does reach a maximum value of

$$(50) \quad . \; . \; . \; . \quad g_c \leqq \frac{1}{\pi}\, g_0, \; g_0 \text{ being the maximum slope,}$$

for the case of a square wave slope variation, namely, when for one-half of the oscillator period $a_1\,(u_{II}) = g\,(u_{II}) = g_0$ and for the other half of the period $a_1(u_{II}) = g\,(u_{II}) = 0$.†

As a matter of fact, if g(t) is non-sinusoidal, a number of different intermediate frequencies $\nu\Omega \pm \omega$ is produced which all carry the undistorted modulation of the signal ω. Their magnitudes are proportional to the amplitudes of fundamental and harmonics of this slope variation respectively. The fundamental β_1^* having always the largest amplitude produces the first order IF, $(\Omega \pm \omega)$, and consequently defines its conversion transconductance $g_c = \frac{1}{2}\,\beta_1^*$. For higher order IF's, $(\nu\Omega \pm \omega)$, different and smaller conversion transconductances might be defined $g_{c\nu} = \frac{1}{2}\,\beta_\nu^*$. This is not usually done, however, as it would not be of any practical significance.

The frequency convertors, the basic principle of which is the variable slope, can therefore immediately be turned into an ordinary amplifier by stopping all slope variation, i.e., by keeping the slope at a constant value which is then identically equal to the " amplification "—transconductance. (Refer to Fig. 11.)

$$g(t) = {}_A a_1\,(u_{II}) = \sum_{\nu=0}^{\infty} {}_B\beta_\nu \, u_{II}^{\nu} = {}_B\beta_0, \text{ for } u_{II} = 0 \;\; \text{(see Fig. 2b).}$$

---

† The fundamental of a square wave of amplitude 1 is equal to $4/\pi$. The amplitude of this square wave is $\frac{1}{2}\,g_0 (0 < g < g_0)$ the fundamental thus becoming $\frac{2}{\pi}\,g$. Since the conversion transconductance equals one-half the fundamental, equation (50) results.

But varying the slope again

$$g(t) = {}_B\beta_0{}^* + {}_B\beta_1{}^* \sin \Omega t + {}_B\beta_2{}^* \cos 2\Omega t + \,.\,. > \sum_{\nu=0}^{\infty} {}_B\beta_1{}^* \begin{matrix}\cos\\ \sin\end{matrix} (\nu\Omega t)$$

a new constant term ${}_B\beta_0{}^*$, fundamental ${}_B\beta_1{}^*$ and harmonic amplitudes ${}_B\beta_\nu{}^*$ of g(t) are obtained. The signal will then be amplified with ${}_B\beta_0{}^*$ as " amplification " transconductance and at the same time converted with ${}_B\beta_1{}^*$ Since the signal is converted into two IF's simultaneously $(\Omega + \omega)$, $(\Omega - \omega)$, one e.g. $(\Omega - \omega)$ being used only, the conversion transconductance for one IF, say $(\Omega - \omega)$ is only one-half of ${}_B\beta_1{}^*$.

Similarly, if $a_3(u_{II})$ is kept constant by applying a constant potential, say, $u_{II} = 0$, so that $a_3 = {}_B\delta_0$, the cross-modulation refers to the amplified signal, i.e., the generation of the new sidebands $(\omega_1 \pm \rho)$ due to the third order term is proportional to a_3, the amplification of the carrier, however, is proportional to a_1, therefore

$$c_r = 3\,\frac{a_3}{a_1}\,U_2{}^2$$

Using the tube as convertor a_3 must also be varied with time, and this variation must contain a fundamental component $\delta_1{}^*$ in order to produce the cross modulation side frequencies for the IF also :

$$\text{if} \quad u_I{}^3 = \,.\,.\,.\,. + p \sin(\omega_1 \pm \rho)\,t + \,.\,.\,.\,. \quad , \quad p = \frac{3}{2} m_2 U_1 U_2{}^2$$

$$\text{then } i_a = \,.\,.\,. + a_3\,(u_{II})\,.\,u_I{}^3 + \,.\,. = \,.\,. + \delta_0{}^*\,p \sin(\omega_1 \pm \rho)\,t$$
$$+ \;\delta_1{}^* \sin \Omega t\,.\,p \sin(\omega_1 \pm \rho)\,t + \,.\,.\,.\,.$$

while the first term of this equation represents the crossmodulation sidebands for ordinary amplification, the second term stands for both IF's simultaneously. Here, again, one-half of $\delta_1{}^*p$ must be taken since only one of the two IF's generated is used.

If this parallelism, existing when a convertor is turned into an amplifier and vice versa, is realised, the formula for amplitude distortion (29) derived for the convertor can be written down immediately for the amplifier :

$$(51) \quad .\;.\;.\;. \quad k = \frac{m}{2 + \dfrac{8a_1}{9a_3}\cdot\dfrac{1}{U_1{}^2}} = \frac{m}{2 + \dfrac{8}{3}\cdot\dfrac{1}{c_r}} \;.\,.\,.\,.\,.\,.$$

U_1 being the carrier of the modulated signal.

A few remarks may be added in this connection.

It has been shown above that the slope variation g(t) may be non-sinusoidal without impairing the performance of the tube, since harmonics of g(t) only produce higher order IF's which are filtered out in the output circuit. It is quite irrelevant how these harmonics have been introduced, whether they are due to a pure sine wave " projected " upon the non-linear g/u_{II}— diagram or whether they may be due to a non-sinusoidal oscillator wave " projected " upon a perfectly linear g/u_{II}— diagram. As a consequence, the wave shape of the local oscillator applied to the mixer does not, in any way, affect the tube's proper performance.

All deliberations set down so far for the two control grid mixer can be applied fundamentally to the one control grid mixer, i.e., to the normal amplifier tube, having impressed on its control grid the vector sum of signal and local oscillator frequencies $(u_I + u_{II})$. In this case there is one characteristic only, the working point of which is shifted about by u_{II}. For any new position of the operating point a new set of Taylor coefficients (a_1, a_2, a_3 . . .) represents the curve, the set being again a function of u_{II}. Therefore, the mathematical treatment described in this article can be adopted without reserve. Also, the actions of u_I and u_{II} upon the current can be interchanged. One may just as well say that u_I shifts the operating point about, etc. This would, however, be vastly more complicated compared with the much simpler method conventionally used in this case. This consists of developing the characteristic in a power series for the bias point used and substituting ($u_I + u_{II}$) in the individual terms of the series. Of course, identical results will be obtained with both methods.

When comparing different H.F. amplifier and mixing tubes qualitatively the ordinary method will certainly be to measure the crossmodulation, and to use these results for the calculation of the ratio a_3/a_1 or δ_1^*/β_1^*. Once this ratio is known, the distortion factor k for envelope distortion can be very precisely caclulàted, and thus the signal handling capacity of the tube. For small amounts of distortion the results of a direct measurement, i.e., audio-analysing the output of a diode fed directly by the convertor, would be doubtful since the diode may distort considerably for smaller inputs (say less than 10 volts) and higher degrees of modulation. On the other hand, raising the voltage level by an H.F. amplifier inserted between convertor and demodulator would introduce new sources of distortion. The measurement of cross-modulation, however, is inherently less liable to inaccuracies due to introduction of new distortions between convertor and measuring device, since it involves measuring the audio fundamental ρ and not its harmonics. Only third order distortions would influence ρ. But these being firstly very small and, secondly, errors of an error, can be neglected as small quantities of second order.

The signal handling capacity is the largest carrier voltage U_2 modulated to a standardised degree m_{st} that may be amplified or converted without suffering more than a standardised modul. distortion k_{st}. Knowing the mathematical relations existing between cross modulation and modulation distortion, it is very easy indeed to determine the signal handling capacity from the usual cross-modulation curves available from tube manufacturers. These curves usually co-ordinate the different values of grid bias voltage U_{GB} with the corresponding values of maximum interfering carrier strength which just produces the permissible crosstalk factor c_r of, say, 6%. Thus c_r is the parameter of these curves. Taking now equation (51) and substituting the standardised values, say $m_{st} = 30\%$ and $k_{st} = 2\%$, determines a certain crosstalk factor

$$c_r = \frac{8}{3}\,\frac{1}{\dfrac{m_{st}}{k_{st}} - 2} = 0{\cdot}205 = 20{\cdot}5\%$$

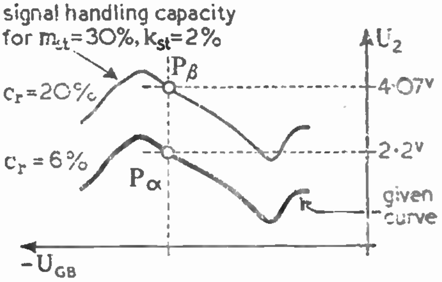
If, now, curves are already measured and given with, say, $c_r = 6\%$, any curve with any other parametric value c_r can be found by shifting the 6% curve parallel to itself along the U_2—axis, provided U_2 has been plotted logarithmically. The position of the new curve is found by taking an arbitrary point on the 6% curve, e.g. P_α (see Fig. 14) which reads 2, 2 volts on the U_2-axis, and then by solving the proportions

$$\left.\begin{array}{ll} c_{r\alpha} = 3\,\dfrac{a_3}{a_1}\,U_{2\alpha}^2 \;\ldots\ldots & 6\% \propto 2.2^2 \\ c_{r\beta} = 3\,\dfrac{a_3}{a_1}\,U_{2\beta}^2 \;\ldots\ldots & 20{\cdot}5\% \propto U_{2\beta}^2 \end{array}\right\} \; U_{2\beta} = 2{\cdot}2\sqrt{\frac{20{\cdot}5}{6}} = 4{\cdot}07 \text{ volts}$$

Thus we find P_β, the corresponding point on the 20·5%-curve which can now be drawn.

In any case, the order of magnitude of a_3/a_1 is about 10^{-2} . . . . 10^{-3} which fully justifies neglecting the quantities concerned in formula (29).

Fig. 14.—Curves for cross-modulation and signal handling capacity *for a frequency changing or amplifying tube.*



c. *Modulation trim.*

If an interfering low frequency voltage $U_\rho \sin \rho t$ is induced in the operating grid circuit containing the desired signal ω the latter appears modulated by this low frequency ρ in the output. This effect may be troublesome if strong electric fields originating from the power supply are allowed to produce voltages in the grid lead, which may occur if the grid circuit is not properly screened.

If $u_I = U \sin \omega t + U_\rho \sin \rho t$ represents the total voltage impressed on the signal grid of the mixer, the table for the combination frequencies can be computed.

Term of equation (20)							
1				2			
$\sum$		$u_I{}^1$		$\sum$		$u_I{}^2$	
1a		1b		2b		2b	
A	fr	A	fr	A	fr	A	fr
β_0^*	0	U	ω	γ_0^*	0	$\frac{1}{2}(U^2 + U_\rho{}^2)$	0
β_1^*	Ω	$U\rho$	ρ	γ_1^*	Ω	$-\frac{1}{2}U^2$	2ω
						$-\frac{1}{2}U_\rho{}^2$	2ρ
⋮	⋮			⋮	⋮	$U \,.\, U_\rho$	$\omega \pm \rho$

The following frequencies and their respective amplitudes are of interest :

$$A\,(\Omega \pm \omega) = \frac{1}{2}\,\beta_1{}^*U$$

$$A\,(\Omega \pm \omega \pm \rho) = \tfrac{1}{2}\gamma_1{}^*\, U \,.\, U_\rho$$

Hence the degree of hum modulation of the signal carrier in the output :

(52) . . . . $$m = \frac{2A(\Omega \pm \omega \pm \rho)}{A(\Omega \pm \omega)} = 2\frac{\gamma_1^*}{\beta_1^*} U_\rho$$

Here again the previously mentioned close analogy between double control grid convertor and amplifier can be drawn, so that the amount of modulation trim for the latter is given by

(52a) . . . . $$m = 2\frac{a_2}{a_1} U_\rho$$

As already indicated above, this effect can relatively easily be remedied by proper shielding of the power supply and the grid circuit. It follows from (52) or (52a) that the degree of hum modulation is independent of the signal voltage so that a later HF or IF stage with higher signal level is not less liable to this type of interference than, say, the first stage with its lowest signal level.

d. *Converter Whistles.*

It is a well-known fact that in a superheterodyne receiver interference whistles may be produced. In the simplest case an image response may be the reason, or some harmonics of a strong local transmitter may combine with some harmonics of the oscillator to give an IF within the pass range of a bandpass filter. The audible whistle tone proper will then be generated in the demodulator stage due to the interaction of the desired IF with the neighbouring undesired IF. It is, however, not proposed to treat this type of interference, which finds its primary cause in the simultaneous presence of the desired and other signals in the grid circuit. The remedy for these phenomena is to be sought mainly in the theory of networks by inserting suitable preselectors, low-pass filters, etc. But whistles may also be produced in the receiver when the desired signal ω only is impressed on the signal grid. Whistles will then be caused by the generation of harmonics of the oscillator and of the signal frequency in the mixer, and their conversion into neighbouring IF's which, on their part, interact with the desired IF to produce beat notes in the demodulator stage. This phenomenon is to be investigated now.

As already shown before, higher IF's of the type $(\nu\Omega \pm \mu\omega)$ are generated in the mixing tube. If the desired IF is given by

(53) . . . . $\Omega - \omega = \omega_{IF}$

Ω being the oscillator, ω the signal frequency, the interfering IF which initially is assumed to equal the desired IF can be defined by

(54) . . . . $\nu\Omega \pm \mu\omega = \omega_{IF}$

For a chosen set of (ν,μ) a simultaneous solution Ω_w and ω_w can be found from (53) and (54). The index w corresponds to the chosen set of (ν, μ).

Allowing the oscillator to drift by an amount $\triangle\Omega$ from its set position Ω_w the desired and the interfering IF'S will no longer coincide but differ by an amount $2\pi f_w$ which then causes a whistle to be produced in the demodulator stage.

$$(\Omega_w + \triangle\Omega) - \omega_w = \omega_{IF} + \triangle\Omega = \omega_{IF1}$$
$$\nu(\Omega_w + \triangle\Omega) - \mu\omega_w = \omega_{IF} + \nu\triangle\Omega = \omega_{IF2}$$

Therefore, the whistle tone is given by

(55) . . . . $2\pi f_W = \omega_{IF1} - \omega_{IF2} = (\nu - 1) \triangle\Omega$

And similarly,

(56) . . . . $2\pi f_W = (\mu - 1) \triangle\omega$

if the signal frequency drifts from its correct value ω_W.

It remains to be demonstrated under which conditions such an interference can really occur. A graphical analysis offers a clearer view in this case and has been chosen. Rewriting (53) :

(53a) . . . . $\omega = \Omega - \omega_{IF}$

is obtained and is represented by the heavy line in Fig. 15. The graph attributes to each oscillator frequency a signal frequency, such that ω_{IF} = const.

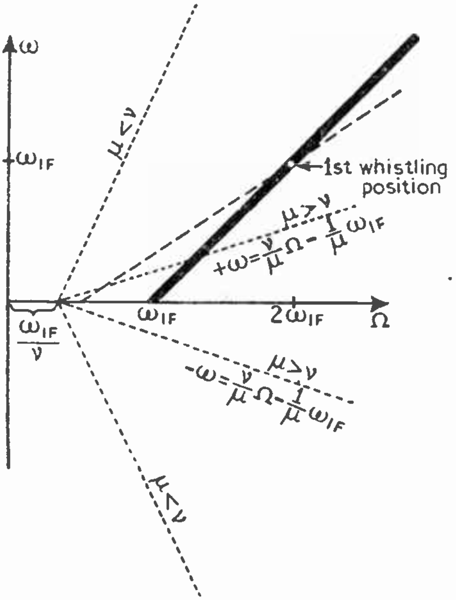


Fig. 15.—Graphical method for evaluating the signal frequencies ω_w at which converter whistles occur.

Rewriting (54) :

(54a) . . . $\mp \omega = \frac{\nu}{\mu} \Omega - \frac{1}{\mu} \omega_{IF}$

and plotting it on the same graph produces the dotted lines shown. A simultaneous solution of (53) and (54) shows up in the diagram as a point of intersection, but only those points can give a physical meaning which lie in the positive quadrant ($\Omega > 0, \omega > 0$). The following conditions for physically possible solutions of (53) and (54) arise from the graph :

(1) Only the plus sign in (54a), i.e., the minus sign in (54) may be taken, consequently the interfering IF can only be the difference between harmonics of Ω and ω.

(2) $\mu > \nu$

(3) $\nu > 1$, (if $\nu = 1$, then simultaneous solution would be $\omega = 0$).

Combining conditions (2) and (3) :

(57) . . . . $\mu > \nu > 1$

gives the condition for physically possible solutions of equations (53) and (54), i.e., each couple of (ν, μ) defines a whistling position of the oscillator such that transmitters with the corresponding signal frequencies ω_w cannot be properly received with the ω_{IF} chosen.

Since μ and ν are positive integers the first whistling position is obtained by substituting the lowest possible values in (57), which then reads $3 > 2 > 1$. Thus the third signal harmonic ($\mu = 3$) and the second oscillator harmonic ($\nu = 2$) produce the first interfering IF. This is the case when

(58) . . . . $\Omega_w = 2\omega_w\,, \quad \omega_w = \omega_{IF}$

as can be shown by substituting the μ and ν values in (53) and (54). The next higher whistling positions are obtained for the values

$$\mu = 4,\ \nu = 2 \quad \therefore \quad \Omega_w = 3\omega_w \text{ and } \omega_w = 0{\cdot}5\ \omega_{IF}$$

and $$\mu = 4,\ \nu = 3 \quad \therefore \quad \Omega_w = 1{\cdot}5\omega_w \text{ and } \omega_w = 2\omega_{IF}$$

This procedure might be continued indefinitely and an infinite number of whistling positions would be obtained ; but, fortunately, the amplitudes of the interfering IF's decrease rapidly with higher values of μ and ν so that the interference tones submerge in the noise level.

It will be instructive to calculate the amplitude of the interference tone at the first whistling position. From Table I it is found that the amplitude of the interfering IF is

$$A_w(\omega_{IF}) = \frac{1}{2} A(2\Omega)\ .\ A(3\omega) = \frac{1}{2}\,{}_B\delta_2{}^* \frac{U^3}{4}\left(1 + \frac{3}{2} m^2\right)$$

whereas the desired IF is

$$A(\omega_{IF}) = g_c\, U = \frac{1}{2}\,{}_B\beta_1{}^*\, U$$

Therefore the latter is quasi-modulated by the former with the modulation depth

(59) . . . . $$m_w = \frac{A_w(\omega_{IF})}{A\ (\omega_{IF})} = \frac{{}_B\delta_2{}^*}{{}_B\beta_1{}^*} \cdot \frac{U^2}{4}\left(1 + \frac{3}{2} m^2\right)$$

(60) . . . . $${}_B\delta_2{}^* = \frac{1}{\pi}\int_0^{2\pi} a_3(t) \sin 2\Omega t\, d(\Omega t)$$

The coefficient ${}_B\delta_2{}^*$ is usually not known, but can be determined indirectly by measurement of m_w. However, it can be estimated that ${}_B\delta_2{}^*$ may be in the same order of magnitude as ${}_B\delta_1{}^*$, but ordinarily it will be smaller still. If in the worst case $\delta_2{}^*/\beta_1{}^* = \delta_1{}^*/\beta_1{}^* = 10^{-2}$, m_w will be in the order of 1% if U is in the order of 1 volt (m = 100%). Taking m = 30% for the average output of the receiver, $m_w = 1\%$ would mean an interference level being about 30 db down. Since this estimate was made for a very unfavourable type of tube it is clear that even the first whistling position which is stronger than the higher one will represent a serious interference only if a strong local transmitter happens to have the same wavelength as the I.F. of the receiving set. (Note that the magnitude of the interference tone increases with the square of the signal voltage.)

B. The Double Control Grid Tube as Modulator.

A double control grid tube can conveniently be used as modulator if one grid carries the modulation frequency ρ and the other the carrier frequency Ω to be modulated (Fig. 16). In the following it will be shown under which conditions this tube can act as a linear modulator.

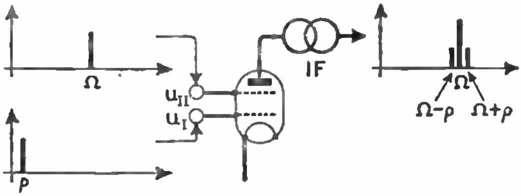


Fig. 16.—The double control grid tube as modulator. *The carrier is just amplified, and the sidebands $\Omega \pm \rho$ are the result of a first order mixing process.*

Let $u_I = U_I \sin \rho t$

be the modulation frequency impressed on grid I and

$$u_{II} = U_{II} \sin \Omega t$$

the carrier frequency applied to grid II, then the following table of combination frequencies is obtained :

Term of Equation (20)															
0				1				2				3			
$\sum$		u_I^0		$\sum$		u_I^1		$\sum$		u_I^2		$\sum$		u_I^3	
0a		0b		1a		1b		2a		2b		3a		3b	
A	fr	A	fr	A	fr	A	fr	A	fr	A	fr	A	fr	A	fr
α_0^*	0	1	0	β_0^*	0	U_I	ρ	γ_0^*	0	$\frac{1}{2} U_I^2$	0	δ_0^*	0	$\frac{3}{4} U_I^3$	ρ
α_1^*	Ω			β_1^*	Ω			γ_1^*	Ω	$\frac{1}{2} U_I^2$	2ρ	δ_1^*	Ω	$-\frac{1}{4} U_I^3$	3ρ
$\vdots$	$\vdots$			$\vdots$	$\vdots$			$\vdots$	$\vdots$			$\vdots$	$\vdots$		

The amplitude of those frequencies giving an undistorted amplitude-modulated wave are

$$A(\Omega) = \alpha_1^*$$

$$A(\Omega \pm \rho) = \frac{1}{2} \beta_1^* \cdot U_I$$

The degree of modulation therefore is

$$(61) \quad . \; . \; . \; . \; . \quad m = \frac{2A(\Omega \pm \rho)}{A(\Omega)} = \frac{\beta_1^*}{\alpha_1^*} U_I$$

Since the second order distortion sidebands are of magnitude

$$A(\Omega \pm 2\rho) = \frac{1}{2} \gamma_1{}^* \frac{U_I{}^2}{2}$$

the distortion factor k will be

$$(62) \quad . \quad . \quad . \quad . \quad k = \frac{A(\Omega \pm 2\rho)}{A(\Omega \pm \rho)} = \frac{1}{2}\frac{\gamma_1{}^*}{\beta_1{}^*} U_I$$

It follows from (62) that the modulation process will be performed without distortion if $\gamma_1{}^* = 0$. Similar arguments as put forward in equations (31) to (34) hold good for this case too, so that the condition for linear modulation is

$$(63) \quad . \quad . \quad . \quad . \quad a_2(u_{II}) = \gamma_0 = \text{const}$$

It can be shown that this condition is perfectly analogous to the corresponding condition for the van der Bijl modulator. It is well known that the latter produces a perfect a-m wave if the characteristic of the single control grid tube is purely parabolic within the range used. Both frequencies being applied to the same grid then produce their fundamentals and second harmonics respectively, and a cross product resulting in the sum and difference frequency. And it is a virtue of the square law characteristic that the amplitude of the second harmonic of one frequency is not influenced by the presence of the other. Assuming a parabola $i_a = a_2u^2$ and adding the shifting voltage v, $i_a = a_2 (u - v)^2 = a_2u^2 - a_2 2v\mu + a_2v^2$, i.e.,, the pure square term a_2u^2 giving the second harmonic and D.C. has remained unaltered by v. But this is exactly what condition (63) demands, viz., for the second order coefficient to be constant. a_2 refers to the characteristic obtained when plotting audio voltage against plate current (i_a/u_I), and a_2 = const. implies that the second harmonic 2ρ of this audio voltage also remains constant. If a_2 varied with the carrier frequency Ω the amplitude of the second harmonic 2ρ would also vary, viz., it would be modulated by Ω. As a result $(\Omega \pm 2\rho)$ would appear as distortion sidebands.

It is, however, not possible in this case to draw such close analogies between double control grid and single control grid tubes as was done in previous paragraphs. The reason being that when the former is used as modulator the carrier is generated by simple amplification, and the sidebands by frequency conversion, whereas in the cases previously examined all frequencies were either converted or simply amplified.

As to the practical side of this particular problem, one advantage of the double control grid over the single control grid modulator (van der Bijl type) is obviously the fact that signal (ρ)- and carrier (Ω)-circuit are practically separated from each other, which in many cases may be of imperative importance. Whether the double control grid modulator provides more depth of modulation and less distortion remains to be investigated in a practical case.

4. Conclusion.

A method has been shown of predetermining the operation of a double control grid tube from its known family of characteristic curves when the two control voltages are given. A general formula establishing the relation between the plate current and both grid voltages was derived :

$$(12) \quad . \quad . \quad . \quad . \quad i_a = f(u_I, u_{II})$$

This equation was applied, firstly, to the case of a frequency converter, and secondly, to that of a modulator.

Regarding the frequency converter, it was found that the third order coefficient of the signal voltage vs. plate current characteristic serves as criterion for its performance if the grid circuit is sufficiently shielded, thus excluding any modulation trim. The following possibilities were investigated :

(1) $a_3(u_{II}) = \delta_0 = \text{const.}$

Ideal conditions are prevailing. The frequency conversion occurs without distortion, and no cross-modulation can take place.

(2) $a_3(u_{II}) = \delta_0 + \delta_1 u_{II}$

The IF generated carries a distorted envelope, the distortion factor of which is given by (29), and the IF is prone to cross-modulation if an interfering modulated carrier can reach grid I of the mixer

(3) $a_3(u_{II}) = \delta_0 + \delta_1 u_{II} + \delta_2 u_{II}^2$

Also the second order IF ($2\Omega \pm \omega$) shows envelope distortion and cross-modulation effects. In addition, the first whistling position now comes into existence, i.e., a strong local transmitter can no longer be properly received if its wavelength happens to coincide with that of the IF of the receiver, for this type of interference is proportional to the square of the signal voltage on grid I.

(4) $a_3(u_{II}) = \delta_0 + \delta_1 u_{II} + \delta_2 u_{II}^2 + \ldots \delta_n u_{II}^n = \sum_{\nu=0}^{n} \delta_\nu u_{II}^\nu$

All higher IF's ($\nu\Omega \pm \omega$), $\nu = 2, 3, \ldots n$ now carry a distorted envelope containing second and third audio harmonics and are prone to cross-modulation. A number of higher order whistling positions occur which can be determined from relations (53), (54) and (57). Their interference effect, however, rapidly decreases with increasing order and decreasing signal amplitude.

In the second case the double control grid tube was used as a modulator and the second order coefficient of the audio voltage vs. plate current characteristic was found to be the criterion of its performance.

(1) $a_2(u_{II}) = \gamma_0 = \text{const.}$

is the condition for undistorted i.e., linear modulation ; but if

(2) $a_2(u_{II}) = \gamma_0 + \gamma_1 u_{II}$

the resulting amplitude-modulated wave shows second order envelope distortions.

APPENDIX

Incidentally, it should be mentioned that equation (12), developed step by step for the plate current as a function of the two control grid voltages u_I and u_{II} is nothing but the Taylor expansion for a function of two independent variables. This must be so since a function can be represented by one, and only one, power series.

Recalling equation (6)

$$i_a (u_I, u_{II}) = \sum_{\mu=0}^{\propto} {}_A a_\mu(u_{II})\, u_I^\mu = {}_A a_0(u_{II})\, u_I^0 + {}_A a_1(u_{II})\, u_I^1 + {}_A a_3(u_{II}) u_I^2 + \ldots$$

the following relations for the functional coefficients ${}_Aa_\mu\,(u_{II})$ will be obtained when Taylor's theorem is applied to each term individually (see also Figs. 1b, 2b, 3b, 4b.).

$$63)\dots\dots a_0(u_{II}) = {}_B\alpha_0 + {}_B\alpha_1\, u_{II} + {}_B\alpha_2\, u_{II}^2 + {}_B\alpha_3\, u_{II}^3 + \dots = i_a\,(u_{II}, o) =$$

$$= i_a\,(0,0) + \frac{1}{1!}\,\frac{\partial i_a\,(o,o)}{\partial u_{II}}\, u_{II} + \frac{1}{2!}\,\frac{\partial^2 i_a\,(o,o)}{\partial u_{II}^2}\, u_{II}^2 + \dots =$$

$$= \sum_{\nu=0}^{\infty} \frac{1}{\nu!}\,\frac{\partial^\nu i_a\,(o,o)}{\partial u_{II}^\nu}\,.\,u_{II}^\nu$$

$$a_1(u_{II}) = {}_B\beta_0 + {}_B\beta_1 u_{II} + {}_B\beta_2\, u_{II}^2 + {}_B\beta_3\, u_{II}^3 + \dots = \frac{1}{1!}\,\frac{\partial i_a\,(u_{II}, o)}{\partial u_I} =$$

$$= \frac{1}{1!}\,\frac{\partial i_a(o,o)}{\partial u_I} + \frac{1}{1!}\,\frac{1}{1!}\,\frac{\partial^2 i_a\,(o,o)}{\partial u_I\,\partial u_{II}}\, u_{II} + \frac{1}{1!}\,\frac{1}{2!}\,\frac{\partial^3 i_a\,(o,o)}{\partial u_I\,\partial u_{II}^2}\, u_{II}^2 + \dots =$$

$$= \frac{1}{1!}\sum_{\nu=0}^{\infty} \frac{1}{\nu!}\,\frac{\partial^{1+\nu} i_a\,(o,o)}{\partial u_I\,\partial u_{II}^\nu}\, u_{II}^\nu$$

$$(63a)\dots\; a_\mu(u_{II}) = {}_B\varphi_0 + {}_B\varphi_1\, u_{II} + {}_B\varphi_2\, u_{II}^2 + {}_B\varphi_3\, u_{II}^3 + \dots$$

$$= \frac{1}{\mu!}\,\frac{\partial^\mu i_a\,(u_{II}, o)}{\partial u_I^\mu} =$$

$$= \frac{1}{\mu!}\,\frac{\partial^\mu i_a\,(o,o)}{\partial u_I^\mu} + \frac{1}{\mu!}\,\frac{1}{1!}\,\frac{\partial^{\mu+1} i_a\,(o,o)}{\partial u_I^\mu\,\partial u_{II}}\, u_{II}$$

$$+ \frac{1}{\mu!}\,\frac{1}{2!}\,\frac{\partial^{\mu+2} i_a\,(o,o)}{\partial u_I^\mu\,\partial u_{II}^2}\, u_{II}^2 + \dots =$$

$$= \frac{1}{\mu!}\sum_{\nu=0}^{\infty} \frac{1}{\nu!}\,\frac{\partial^{\mu+\nu} i_a\,(o,o)}{\partial u_I^\mu\,\partial u_{II}^\nu}\, u_{II}^\nu$$

By mere comparison the α, β, γ, δ coefficients can be determined, e.g. :

$$\left.\begin{matrix}\mu = 2\\ \nu = 3\end{matrix}\right\}\;\dots\dots\; {}_B\gamma_3 = \frac{1}{2!}\,\frac{1}{3!}\,\frac{\partial^5 i_a\,(o,o)}{\partial u_I^2\,\partial u_{II}^3} \qquad \text{etc.}\;\dots\dots$$

Substituting relation (63*a*) in equation (6) :

$$(64)\dots\; i_a(u_I, u_{II}) = \sum_{\mu=0}^{\infty} \frac{1}{\mu!}\sum_{\nu=0}^{\infty} \frac{1}{\nu!}\,\frac{\partial^{\mu+\nu} i_a(o,o)}{\partial u_I^\mu\,\partial u_{II}^\nu}\, u_{II}^\nu \cdot u_I^\mu$$

$$= \sum_{\substack{\nu=0\\ \mu=0}}^{\infty} \frac{1}{\mu!\,\nu!}\,\frac{\partial^{\mu+\nu} i_a(o,o)}{\partial u_I^\mu\,\partial u_{II}^\nu}\, u_I^\mu\,.\,u_{II}^\nu$$

This last equation (64) already shows one possibility of writing down Taylor's theorem for two independent variables. Another perhaps more convenient form may be derived from (64) by means of a simple transformation of the index ν.

Putting $m = \mu + \nu$, i.e. $\nu = m - \mu$

observing that $m \geqq \mu$ and substituting in (64)

$$(64a)\,.\, i_a(u_I, u_{II}) = \sum_{\substack{m=0\\ \mu=0}}^{\infty} \frac{1}{\mu!\,(m-\mu)!}\,\frac{\partial^m i_a(o,o)}{\partial u_I^\mu\,\partial u_{II}^{(m-\mu)}} \cdot u_I^\mu\, u_{II}^{m-\mu}$$

Since $\frac{1}{\mu!} \cdot \frac{1}{(m-\mu)!} = \frac{1}{m!}\binom{m}{\mu}$ equation (64a) becomes :

$$i_a(u_I, u_{II}) = \sum_{\substack{m=0\\ \mu=0}}^{\infty} \frac{1}{m!}\binom{m}{\mu} \frac{\partial i_a{}^m(o, o)}{\partial u_I{}^\mu \ \partial u_{II}{}^{(m-\mu)}} u_I{}^\mu \, u_{II}{}^{m-\mu}$$

And introducing for convenience the operators

$$D_I{}^\mu = \frac{\partial^\mu}{\partial u_I{}^\mu} \text{ and } D_{II}{}^{m-\mu} = \frac{\partial^{m-\mu}}{\partial u_{II}{}^{m-\mu}}$$

$$i_a(u_I \, u_{II}) = \sum_{\substack{m=0\\ \mu=0}}^{\infty} \frac{1}{m!} \binom{m}{\mu} D_I{}^\mu \, D_{II}{}^{m-\mu} \, i_a(o, o) \, u_I{}^\mu \, u_{II}{}^{m-\mu} =$$

$$= \sum_{m=0}^{\infty} \frac{1}{m!} \sum_{\mu=0}^{\infty} \binom{m}{\mu} (u_I D_I)^\mu (u_{II} D_{II})^{m-\mu}. \, i_a(o, o)$$

Bearing in mind that $\mu < m$, it appears that the sum over μ is the binominal theorem, so that :

$$i_a(u_I, u_{II}) = \sum_{m=0}^{\infty} \frac{1}{m!} (u_I D_I + u_{II} D_{II})^m \, i_a(o, o)$$

(65) . . $i_a(u_I, u_{II}) = e^{u_I D_I + u_{II} D_{II}} \, . \, i_a(o, o)$

which represents another form of Taylor's expansion for two independent variables.

Equation (65) written out then reads :

$$i_a \, (u_I, u_{II}) = i_a \, (o, o) + \frac{\partial i_a \, (o, o)}{\partial u_I} u_I + \frac{\partial i_a \, (o, o)}{\partial u_{II}} u_{II} +$$

$$+ \frac{1}{2!} \left[\frac{\partial^2 i_a \, (o, o)}{\partial u_I{}^2} u_I{}^2 + 2 \frac{\partial^2 i_a \, (o, o)}{\partial u_I \, \partial u_I} u_I \, u_{II} + \frac{\partial^2 i_a \, (o, o)}{\partial u_{II}{}^2} u_{II}{}^2 \right] + \, . \, .$$

$$= {}_B\alpha_0 + {}_B\beta_0 \, u_I + {}_B\alpha_1 \, u_{II} + {}_B\gamma_0 \, u_I{}^2 + {}_B\beta_1 \, u_I \, u_{II} + {}_B\alpha_2 \, u_{II}{}^2 +$$
$$+ {}_B\delta_0 \, u_I{}^3 + {}_B\gamma_1 \, u_{II} \, u_I{}^2 + {}_B\beta_2 \, u_{II}{}^2 \, u_I + {}_B\alpha_3 \, u_{II}{}^3 + \dots\dots$$

And equation (12) written out would read :

$$a \, (u_I, u_{II}) = {}_B\alpha_0 + {}_B\alpha_1 \, u_{II} + {}_B\alpha_2 \, u_{II}{}^2 + \dots + {}_B\beta_0 \, u_I + {}_B\beta_1 \, u_{II} \, u_I + {}_B\beta_2 \, u_{II}{}^2 \, u_I + \dots$$
$$\dots + {}_B\gamma_0 u_I{}^2 + {}_B\gamma_1 \, u_{II} \, u_I{}^2 + {}_B\gamma_2 \, u_{II}{}^2 u_I{}^2 + \dots$$
$$+ \, {}_B\delta_0 u_I{}^3 + {}_B\delta_1 u_{II} u_I{}^3 + {}_B\delta_2 u_{II}{}^2 u_I{}^3 + \dots$$

A comparison of the last two results demonstrates their identity as well as their only difference, viz. the order of sequence of the individual terms.

A PROPOSAL

recommending the formation of a

BRITISH RADIO RESEARCH INSTITUTE

Submitted by

THE BRITISH INSTITUTION OF RADIO ENGINEERS

to the Radio Industry and Government of Great Britain
*as a contribution toward post-war prosperity.**

(*a*) Introduction.

Increased research in industry has been discussed and advocated by many influential bodies as part of the nation's reconstruction programme. Proposals have been made by members of both Houses of Parliament in addition to recommendations made by such bodies as the Federation of British Industries. All recommend the development of research associations and the payment of increased grants by the Department of Scientific and Industrial Research; comparatively new industries, such as aeronautical and radio engineering, have been especially mentioned.

The Parliamentary and Scientific Committee has been frequently addressed on the importance of research, and it has been emphasised that if Britain's position in the world is to be maintained, research in many industries will have to be undertaken on a scale not hitherto contemplated. Their reports[1] have stressed the fact that applied science cannot live on the fundamental discoveries of past generations and whilst the search for truth has always been an essential accompaniment to higher education, fundamental research cannot always be confined to universities. Industrial and Government research organisations also have an essential part to play.

In March, 1943, the Council of the British Institution of Radio Engineers appointed a Committee "To consider proposals for the formation of a British Radio Research Institute, and to make such recommendations as they feel necessary to the Government and to radio manufacturers."

The following is a condensed report of their deliberations and their recommendations. It is believed that these are the first proposals recommending co-operative research in British Radio Engineering.

(*b*) General.

1. The benefits of science are only made available to humanity through industry, but without previous fundamental discoveries and the formulation of scientific knowledge there can be no such outcome.[2] In order to improve and even to maintain British

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* The proposal was submitted in January, 1944.

eminence in radio and electronics, research in the various branches of the science will have to be undertaken on a scale not contemplated in the pre-war era.

2. Fundamental research is impossible of completion, and often of initiation, when contingent upon immediate financial result. Continuous research is essential to industrial prosperity and must not be subject to spasmodic effort caused by trade fluctuation.

3. Application of the results of fundamental research is essential for successful private enterprise. Thus, basic research aids industry by eliminating duplicated work whilst leaving enterprise unfettered in development of any given project—a step which is subject to constant improvement by normal trade competition.

4. Individual or part encouragement of fundamental research is not enough if industrial prosperity is to be achieved. The scheme worked out by the Institution of Automobile Engineers for the motor industry could well be adopted by the radio industry, although it is felt that the necessary co-operation between Government, industry and the Research Institute, would be best fostered by forming the Board of representatives as indicated in paragraph 11.

5. Government participation in the work and direction of research associations is essential. In this connection the Institution refers to the valuable assurance given in the House of Lords by the Paymaster-General, Lord Cherwell (20/7/43) "that it is the policy and intention of H.M. Government to increase their assistance to pure research," and that he would "welcome any developments in industry in a similar direction."

6. The success of present research associations is largely due to their specialisation, e.g., Cast Iron Research Association *and* Non-Ferrous Metals Research Association, in addition to the Iron and Steel Industrial Research Council (see page 11). Any merging or extension beyond their sphere of existing associations will involve limitations of the rights of members of such Associations to whom, as the F.B.I. report states, the Research Association has a prime responsibility.

7. Whilst recommending extension of Research Associations, the F.B.I. report also stresses that "the interdependence of industries is such that many individual industries and their Research Associations are also members of research associations representing other industries with which they have relations either as purchasers or suppliers. This is a most valuable feature of the Research Association movement *and one which should be extended.*" The radio industry would benefit from such liaison through the proposed Research Institute.

(*c*) The Proposal

In proposing the formation of a British Radio Research Institute, the Institution recommends that :—

8. The *function* of the Research Institute be the pursuit of basic research of the type that has hitherto suffered restriction owing to its high cost, absence of obvious or immediate practical applications, or the poor prospect of early financial returns.

9. Progress *reports* describing the results of the work of the Institute be published at regular intervals and that no restriction be placed upon access to these reports or upon the private, commercial or industrial employment of the information contained therein.

10. The Institute be *financed by* industrial subscriptions supplemented by a Government grant of at least *equal* amount.

11. The work of the Institute be *directed by* an impartial Board comprising representatives of :—

(*a*) Governmental authorities (e.g. G.P.O. and D.S.I.R.), B.B.C. *and the Services.*

(*b*) The Industry.

(*c*) The Brit.I.R.E. and associated professional institutions.

(*d*) Universities of the Empire.

12. The research *programme* be revised periodically by the Board, and new subjects added at any time according to demand. In this way, a " subject of research " will become a broad field of continuous investigation, frequently leading to investigation of other problems.

13. In addition to a permanent qualified scientific staff, arrangements be made through industry and the universities for the assistance and engagement of *extra-mural workers.*

(*d*) Benefits to State and Industry.

14. The advancement of radio and electronic science would be freed from the limitations hitherto imposed by restricted finance, duplication of original research work, spasmodic trade fluctuations, etc.

15. Competitive private enterprise would be stimulated and the intake of high grade technical personnel increased. It would remain the province of private enterprise to develop the practical and industrial applications of the scientific results flowing from the Research Institute. Thus, the need for separate research departments associated with individual firms would be enhanced. But the broad advancement of science would not be impeded by their necessarily limited interests ; instead, they would add a wealth of practical detail to the original work of the Institute.

16. The pre-war hiatus between industry, the Government and scientists would be effectively bridged by the proposed Board.

The constitution and work of the Board would admirably fit it to discuss, in proper perspective, such matters as industrial development, State security, patent protection and the desirability and extent of Government control. The Board would thus offer valuable possibilities as an advisory body without in any way encroaching upon the legitimate domain of private enterprise or of independent Government action.

17. It is in no way proposed to restrict the application of private research and, in fact, the publication of the Institute's progress reports will assist and stimulate private research which may still be carried on by independent firms.

18. The work of certain scientists on radio echo phenomena, which originally was mainly of academic interest but subsequently proved to be of immense practical value, can be taken as typical of the work to be undertaken by the Institute. As is well known, the outcome of this particular research has proved to be the basis of new industries producing a variety of equipment having wide applications in times of peace as well as in war. Moreover, the applications of the principle have by no means been exhausted.

19. New knowledge, carrying with it the possibility of new industries, would be continuously sought and be available for the free use of manufacturers to develop practical applications of the scientific principles.

20. The necessity for private research departments will not be reduced, but the availability of undeveloped basic knowledge will give such departments a far greater opportunity for returning a dividend. Private enterprise and competition will be stimulated when the emphasis is shifted from price reduction to the development of new fields of manufacture. A broadening field of activity is obviously more advantageous than growing competition within a fixed domain.

21. It should be noted that whereas the information issued by the Institute will not necessarily be protected by letters patent, those developing practical devices based upon this information will be free to apply for patent rights if they wish.

22. The application of radio technique to fields other than broadcasting is capable of considerable development and therefore the potential absorption of labour is considerable. Furthermore, the necessity for large numbers of trained radio technicians in time of war has been proved, and the direct method of ensuring that the country shall not be deficient in this respect is to develop the applications of electronics to the fullest extent.

23. The work of the proposed Institute will not duplicate or encroach upon that of the existing Government Research Establishments, but it is very possible that its discoveries may increase their activities.

24. Application of electronics to industry classifies radio as a " master key " industry and provides some of the tools with which our scientists work. Radio research must, therefore, receive adequate encouragement if Britain is to build up the intensely scientific industrial system which must be the foundation of her national and economic strength in the future.

25. Finally, it must not be overlooked that the benefits of technical development are not confined to those within the affected industry. The products of original research are ever-widening and give constant impetus to industry as a whole—hence the success of other research associations.

(*e*) Finance.

26. The tables on page 11 emphasise the steady growth of research associations and the increasing financial support given by old-established industries ; the individual income figures are representative of *peace-time* conditions, i.e. before war-time expansion programmes. In such fields as the radio industry, war-time expansion must be at least maintained, and this will obviously necessitate greater attention to research.

27. The contribution of industry to research associations was increasing before the war and support is now being given to the principle of larger contributions being made in the future to co-operative research programmes.[3] Assuming, however, the turnover to be only 20 million pounds for the radio industry, an allocation of a ¼ of 1% would give, with Government assistance, an income comparable with other Research Associations.

28. If subscribing membership is open to all British industrial undertakings in the British Commonwealth which produce, manufacture or use electronic equipment, the income of the Research Institute would be comparable with the support given to any other association, whilst at the same time making the field of research inexhaustible.

29. Readiness is needed on the part of medium sized and small firms to participate in this group research. Large membership is essential if the Research Institute is to secure the financial support necessary for successful operation.[4]

30. The Department of Scientific and Industrial Research is responsible for certain Government Research establishments in addition to supervising Government grants to research associations. The estimated total expenditure of the Department for 1942-3 is £678,596 as against £657,850 for 1937 and £446,214 for 1928.[5] The Government recognises the need for a large scale expansion of the work of D.S.I.R. and has already stated that Government grants to research associations are given if sufficient support is given by the industry benefiting from the work of such research institutes.

31. American advantages in radio research are well exemplified by the Massachusetts Institute of Technology, which has made a tremendous contribution to radio progress and is State supported.[6] In order to give full opportunity for equivalent British fundamental research, an adequate State grant is essential.

(*f*) Present-day Radio Research.

32. Between 1925 and 1935 the State contribution to radio research came through the Radio Research Board, largely concerned with the effects of atmospherics on radio. War has brought about a remarkable transformation in British radio research activities.

33. The Radio Board of the War Cabinet is the present supreme inter-Service and inter-Departmental radio authority of His Majesty's Government and serves to co-ordinate research, development and production as well as Service radio problems. The Operations and Technical Radio Committee provides a common meeting ground between the Services and the scientists and engineers. The Production Planning Radio Committee has the task of reconciling the claims of the Services for radio equipment with the country's ability to produce it on time. Its right arm is the Radio Production Executive. whose planning and co-ordinating staff directs the work of the inter-Service production committees concerned with components, valves and radio equipment. Lastly, there is the Central Radio Bureau also under the ægis of the Board, which deals with the collection and distribution of scientific and technical information.

34. The supremacy which Britain has now acquired is largely due to the Government's interest in radio devices, as instanced by the present Radio Board. If that lead is to be maintained vast sums will have to be expended continuously on research and development.

35. Privately run research laboratories have not quite the same function as a nationally organised research institute. By the very nature of their organisation, private research is apt to be partial and specialised in its application. They also depend for the volume of their work upon the prosperity or otherwise of their particular industry. As in war, such research needs supplementing by national co-operation.

36. Properly equipped research laboratories are very elaborate and expensive, and without Government assistance it is impossible to set up adequate research stations.

37. In order to increase the volume of private and Government radio research, both pure and applied, it is necessary to introduce some national link to make the best use of our available resources, both in finance and man-power. This will facilitate our competing successfully with other nations.

38. Devices such as the cyclotron and the electron microscope cost far more to erect, even experimentally, than is normally spent by the average firm on all of its research. Similar fields are investigated by only the very largest firms, mainly in U.S.A., and results do not always become generally available.

39. Unfortunately, and largely through reluctance to plan ahead and to standardise, British technical skill does not reach such heights as it could, nor are we able to make our products as universally excellent as we would if there was more co-operation between Government and the scientists.

(*g*) National Prosperity.

40. Apart from coal, practically our only indigenous industrial asset is our standard of technique and our workers' skill. This expresses itself at the highest level in the production of fine instruments—particularly in recent years in radio instruments, which have a very high export value in relation to the imported raw materials they contain.

41. The Radio industry is already concerned with the drive for increased exports. From the technical point of view an essential asset in securing and retaining export markets is the maintenance of at least the high standard of research that has been reached during the war. The need for such a policy is one of the strongest incentive to Government participation.

42. Research and development, stimulated by the needs of war, have made giant strides over the past five years, *and the pace is quickening*. Britain is at present abreast of other countries, but the post-war conception of research cannot return to the basis on which radio primarily meant manufacturing receiving sets.

43. During the war radio has graduated into a highly important industry. In the post-war era it should be supplying capital goods on a scale equal to many of the older industries ; not only should the range and quality of its consumer goods be very different from anything known before, but essential instruments and devices for other industries must be provided if British scientific and industrial progress is to be maintained. For all this development co-operative research is essential.

(*h*) Empire Development.

44. It is strongly advocated that opportunity for participation in the work of the Research Institute shall be provided for all countries in the British Commonwealth. Such collaboration in research will materially aid development of communications and the prosperity of the entire Empire.

45. The Australian radio industry supplies all Australia's needs,[7] but that Dominion reciprocates Britain's need for a central

research institute which is capable of undertaking more work than is financially possible by any one private radio concern in any country comprising the British Commonwealth.

46. The demands of war have created plants for the manufacture of radio apparatus throughout the British Commonwealth. Canada, South Africa and India will encourage radio research to support their own, even though small by comparison, radio industries. Scientifically, the need for such out-stations is eminently desirable and can be admirably organised by the Board of the British Radio Research Institute.

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INCOME OF RESEARCH ASSOCIATIONS, 1936-37.

Income figures taken from the Report of the Department of Scientific and Industrial Research for the year 1936-37.

Research Association	Income £		As per cent. of Net Product of Industry
British Colliery Owners	5,030		0·003
British Cast Iron	14,865	£66,681	0·07
British Iron and Steel Federation	51,816		
British Non-Ferrous Metals	28,521		0·12
Institution of Automobile Engineers	16,763		0·03
British Electrical and Allied Industries	81,073		0·18
British Refractories	9,909		0·06*
British Food Manufacturers	4,668	£24,368	0·03
Cocoa, Chocolate, Sugar, Confectionery and Jam Trades	6,891		
British Flour Millers	12,809		
British Paint, Colour and Varnish Manufacturers	15,998		0·18
British Rubber Manufacturers	11,360		0·06
British Leather Manufacturers	19,387	£24,424	0·09
British Boot, Shoe and Allied Trades	5,037		
British Cotton Industry	80,239	£119,440	0·08
Wool Industries	19,913		
Linen Industry	19,288		
British Launderers	10,818		0·015†
Printing and Allied Trades	10,130		0·014
British Scientific Instrument	9,257		0·15
Total	£433,772		

*Of all the Pottery Industry. † Of all the Clothing Industry.

TOTAL GOVERNMENT GRANT AND INDUSTRIAL CONTRIBUTION TO THE RESEARCH ASSOCIATIONS.

To meet the difficulties of the many small firms in this country the Department of Scientific and Industrial Research after the last war initiated the scheme of Research Associations. These were supported jointly by the Treasury and by firms in the industry, originally on a " pound for pound " basis but later at half the rate on the Government side.

Year	No. of Associations	Income from Industry £000	Income from Government £000	Total £000	Per cent. Increase or Decrease on Previous Year
		£	£	£	
1920	17	96	65	161	
1921	21	108	84	192	+19
1922	21	111	93	204	+ 6
1923	21	121	103	224	+10
1924	21	113	100	213	− 5
1925	20	118	88	206	− 3
1926	21	111	78	189	− 9
1927	19	115	60	175	− 8
1928	19	124	54	178	+ 2
1929	20	153	79	232	+25
1930	20	158	82	240	+ 3
1931	20	160	88	248	+ 3
1932	20	167	68	235	− 5
1933	19	174	59	233	− 1
1934	19	191	86	277	+19
1935	19	232	109	341	+23
1936	18	250	127	377	+11
1937	20	—	—	—	—
1938	22	—	177	—	—

Figures from the Department of Scientific and Industrial Research.

The British Institution of Radio Engineers

TRANSFERS AND ELECTIONS TO MEMBERSHIP

Since the issue of the Year Book, the Membership Committee has received 64 proposals for election to various grades of membership and 49 applications for Studentship Registration. The following transfers and elections were effected by the General Council at their meeting held on the 5th May, 1944 :—

Transferred from Associate Member to Member

BRENNAN, Hugh, B.Sc.	Gateshead, 9
DIMMICK, John, B.Sc.	London, S.E.27
TAYLOR, Francis, Lt.-Colonel, B.Sc.(Eng.)	Droitwich Spa

Elected to Member

DAVIS, Basil Montefiore, Sqdn. Ldr.	London, W.1
FRIEDLAENDER, Ernst Rudolf	Manchester, 20
WILLIAMS, Emrys, Ph.D.,B.Eng.	Newcastle-upon-Tyne
WILSON, William, D.Sc., B.Eng.	Birmingham

Transferred from Associate to Associate Member

BURROW, Jack	Rotherham, Yorks.
LEETE, David Latcham, B.Sc.	London, N.14

Elected to Associate Member

ALTY, Henry Brian	Manchester
DURHAM, William Charles	Farnborough, Hants.
GOODYEAR, Sydney	Brookmans Park
HOWARD, Robert William	Hull
MORT, Jesse, B.Sc.(Hons.)	Golbourne, nr. Warrington
TAYLOR-SMITH, William	Edgware, Middx.
THWAITES, George Percy, B.Sc.(Eng.)	Chislehurst
VICK, Ernest Henry	Douglas, I.O.M.
WELLMAN, Kenneth Purver	Orpington, Kent
WORTHY, Sydney Albert, F/O.	Swindon, Wilts.

Reinstated as Associate Member

BRANCZIK, Eric Anthony Charles	London, W.4

Transferred from Graduate to Associate

BARRY, Dennis George	Oxshott
HOWELL, Kenneth Lamb	London, W.3

Transferred from Student to Associate

JONES, John William	Middlesbrough
GWYNN, Norman Thomas	Twickenham

Elected to Associate

ALIAGA-KELLY, Thomas William D.	Dublin
COLTON, Norman Kenneth	Alness, Ross-shire
CRAVEN, John Harold	Burnaby Lake, British Columbia
ERASMUS, Errol Do Preez	Germiston, South Africa
EVANS, Kenneth William	Derby
FISHER, Eric George	Chester-le-Street
GOTHAM, Kenneth Victor, B.Sc.	West Bromwich
HANNAM, William Harold	Leominster
JONES, Harry, Flt./Lt.	Leicester
MILLER, Alfred, B.Sc.(Eng.)	London, S.W.1
ORCHARD, Henry John	West Bromwich
OSWALD, Robert Raine	Leicester

PEDDIE, Leslie	Portsmouth
THOMSON, Francis Paul	Welwyn Garden City
TRAINER, Allan Lorraine, B.Sc.	Hexham
TRIER, Robert Henry, B.Sc.(Eng.)	Sidcup
WILLIAMS, Gordon	Portsmouth

Reinstated as Associate

DEERING, John Edward	London, E.18

Student Registrations

ACTON, John Reginald	Beaconsfield
ARNOLD, Frederick John	Swindon
BARNET, Peter Alan	London, W.C.1
BASSETT, William George	Dublin
BEAUCHAMP, Kenneth George	Coventry
BELLCHAMBERS, William Henry	Gosport
BROMBERGER, Berthold	Palestine
BROWN, Thomas Irwin	Dublin
CATLOW, Robert Harvey	Leicester
CHAPMAN, Stanley	Poynton, Cheshire
COOKE, William Bert	Letchworth
CORMACK, Maurice	Liverpool
CRABTREE, James Edward	Derby
DANIELS, Ronald Edward	Seven Kings
DUTHIE, Rae Lawrence	Glasgow
ECCLES, Claude Llewellyn	Birmingham
ERDOS, George	Loughborough
FAIRALL, Ronald	London, S.W.4
FLATMAN, Bernard Clive	Saxmundham
FLEMING, William Calderwood	Coventry
GENTRY, Maurice Dudley	London, W.3
GLADSTONE, Leslie Harold	Coulsdon
GRIFFIN, Percy Albert	London, W.5
HAYWOOD, Thomas Duncan	Leeds
HISCOCK, David	Slough
HUTTON, James Alan	Hull
JENSEN, Thomas Henry	Plymouth
KEAY,John McLachlan	Derby
LIVINGSTONE, David Forsyth, B.Sc.	Cupar, Fife
LUCKETT, William Roy	Hereford
MARTIN, Linden Herbert	Opapa, New Zealand
MICHIE, Joseph Lawrence	Skelmersdale
MILLS, Kenneth Douglas	Reading
MUTHANNA, Muruvanda Pennappa	Mysore, India
PETTY, Walter	Lancaster
POOLEY, Eric Kenneth	Ipswich
PUTTOCK, Aubrey Dennis	Matfield
RICHARDSON, Ellis	Cheadle
RICKERS, Robert Thomas	Wallasey
ROBERTSON, Reuben	Haifa, Palestine
ROBERTSON, William	Glasgow, S.2
SUMNER, Geoffrey Charles	Carnforth
THOMPSON, Charles Leslie	Scunthorpe
TROST, John Rudolf	Hove, 4
WALKER, Clarence Henry, B.Sc.	Lincoln
WILLIAMS, Raymond	Bridgnorth
WILSON, Frank	Rochdale

The British Institution of Radio Engineers

STABILISING ELECTRONIC CIRCUITS

by

M. M. Levy (*Associate Member*).*

A paper read before the London Section of the Institution on November 26th, 1943.

INTRODUCTION

"There is a continuous need for improving more and more as time goes on the stability of certain types of electrical circuits, the performance of which is liable to be affected by variations in the source or sources of supply, and the writer had the task of improving some of these circuits.

Successful results were obtained in some cases. In the case of variable frequency oscillators, two arrangements were found, giving good stabilisation of the output voltage and current, respectively. For sensitive valve voltmeters, variation in the zero was eliminated by convenient arrangements, and the sensitivity was made independent of fluctuations in the supply voltage.

Means for balancing out the effects of power supply variations generally were also studied with good results. In some cases variations of 20 per cent. could occur in the high tension voltage without producing any appreciable effect in the performance of a stabilised circuit.

The paper describes these various arrangements, and for convenience has been divided into two parts; the first part deals with problems concerned with selective amplifiers and oscillators, and the other part with problems concerning instabilities produced by mains voltage variations.

The opportunity has been taken to refer to some earlier work done by the writer during the years 1930 to 1932, on the application of negative feedback to stabilisation of selective amplifiers, on similar lines to the well known work by Dr. H. S. Black in the United States."

PART I

SOME PROBLEMS CONCERNING SELECTIVE AMPLIFIERS AND OSCILLATORS

SUMMARY

1. USE OF NEGATIVE FEEDBACK TO INCREASE THE STABILITY OF SELECTIVE AMPLIFIERS

The selectivity of a selective amplifier can be increased by positive feedback. But this produces a great deal of instability. By using negative feedback, the selectivity can be increased with no increase of instability. The writer describes a selective amplifier with which he studied in 1930-1932 the general properties of negative feedback applied to selective amplifiers, and, by extension, to oscillators.

2. AN OUTPUT VOLTAGE STABILISER FOR VARIABLE FREQUENCY OSCILLATORS

This circuit is an improvement of the type of stabiliser in which a conveniently biased diode shunts the oscillator. Here a triode is used instead of the diode together with a detector amplifier valve amplifying and then transmitting to the grid all variations of voltage.

The circuit is very efficient; oscillator voltage variations of more than 100 per cent. are reduced to less than 1 per cent.

A practical circuit used with a multirange oscillator is described. The stabilising circuit drains a total H.T. current of less than 7 milliamperes and gives a perfect stabilisation from 30 K.C. to 10 M.C. In each range the output voltage is constant within ·05 decibels.

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* Standard Telephones and Cables, Ltd.

3. AN OUTPUT CURRENT STABILISER FOR VARIABLE FREQUENCY OSCILLATORS

The high frequency current to stabilise flows in a convenient thermo-couple connected to a micro-ammeter. A special device is added to the meter so that an A.V.C. voltage as high as 20 volts D.C. is produced when the needle approaches a given point on the scale. This voltage is used in a feedback circuit to stabilise the meter deflection.

A practical meter control unit is described. The unit has been used to stabilise the H.F. current produced by the oscillator of a Q meter. Variations of more than 100 per cent are reduced to less than 3 per cent.

1. USE OF NEGATIVE FEEDBACK TO INCREASE THE STABILITY OF SELECTIVE AMPLIFIERS

The stabilising properties of negative feedback applied to wide band amplifiers is well known. Mr. Hill (12)* gave a very interesting account of the works of Black, Nyquist and Bode, and Mr. Reyner (11) gave details of some practical applications.

The properties of negative feedback applied to selective amplifiers has not received so much attention, and some early publications on this subject do not seem to be known.

The writer realised the important stabilising properties of negative feedback in 1930[1, 2, 4] when attempting to produce reliable highly selective amplifiers at low frequencies. He was trying to produce a variable frequency selective amplifier having a selectivity and a sensitivity practically independent of the frequency of selection. For this purpose, he thought to use a series tuned circuit because a tank circuit has an impedance which varies when the tuning frequency is varied by means of a variable capacity. He thus made the feedback circuit represented in Fig. 1[4]. The feedback is positive and adjustable so that the selectivity can be increased more or less. But he found this circuit very unstable at the high selectivities required for his work. This is due to the fact that the tuned circuit is in series with a resistance circuit of high value so that its Q is very poor. The positive feedback increases the selectivity, but produces at the same time a great instability. He then thought that maybe the use of negative feedback—if it was possible to find a way to increase the selectivity by negative feedback—will act in the opposite way and produce something very stable. He decided then, with Professor Leon Brillouin, to study the properties of positive and negative feedback

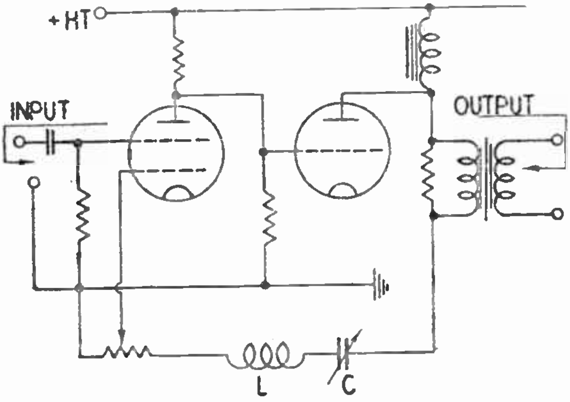

Fig. 1.—Positive feedback selective amplifier circuit used in 1930-1932 *to study the properties of positive feedback. An increase of feedback increases proportionally the selectivity, the instabilities, and the non-linear distortions.*

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* The reference numbers refer to papers detailed in the reference list given at the end of Part I.

applied to selective amplifiers, and they chose a convenient circuit for this purpose.[1]

This circuit is represented in Fig. 2. The feedback is produced by a bridge circuit, one arm of which contains the tuned circuit. The frequency of selection can be varied by means of the condenser which is of a variable type. The circuit being built for acoustic frequencies, the coil is of great value by necessity. To get a reliable coil, it was decided to use a wire wound one, and to obtain the same resistance at all acoustic frequencies, a very fine wire was chosen. The Q of the tuned circuit was very poor.

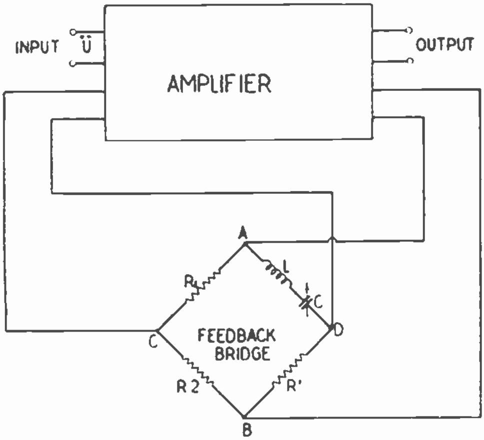

Fig. 2.—Bridge Feedback circuit used in 1930-1932 to study the properties of negative feedback. This circuit combines a selective negative feedback which improves the Q of the tuned circuit and a feedback independent of frequency which may be made positive or negative.

This circuit was very convenient for experimental studies and presented the big advantage to combine a selective feedback and a feedback independent of frequency. The amount of each of these feedbacks was easily adjustable and the second could be easily made positive or negative.

This can be understood clearly with the help of the vector diagram of Fig. 3. The voltage applied to the input is represented by vector u, and it is assumed that the output voltage feeding the diagonal AB is 180° out of phase with u. CD is the feedback vector and can be considered as the resultant of CoD and CCo. When the frequency varies, point D moves on a circle of diameter CoB. Point D coincides with Co for the resonance frequency and moves towards B when the frequency goes far off. The two components CoD and CCo of vector CD are very different. Vector CoD varies in amplitude and phase with frequency and will be called the selective feedback ; whilst vector CCo is fixed and will be called the feedback independent of frequency.

The selective feedback is nil at the resonance frequency, and has a negative feedback component which increases in value when the frequency goes far off from the resonance frequency. Thus, this feedback reduces the sensitivity of the circuit for frequencies far from the resonance, i.e., this feedback increases the selectivity without changing the characteristics of the circuit for the resonance frequency. The amplitude of CoD, and thus the increase of selectivity, is proportional to the sensitivity of the amplifier. The practical effect of the selective feedback is to increase the Q of the tuned circuit.

The feedback independent of frequency CCo has an amplitude which can be easily adjusted by varying one of the resistances of the bridge. It can be made positive or negative, and thus increase or decrease the sensitivity of the circuit.

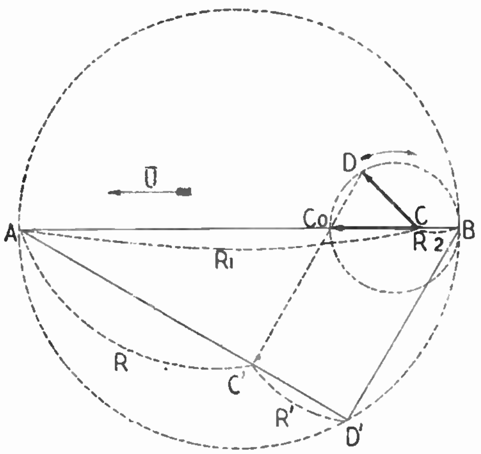

Fig. 3.—Vector diagram corresponding to the circuit of Fig. 2. CoD is the selective feedback vector, CCo the feedback independent of frequency and CD the resultant feedback vector for an input vector u.

With this circuit, the writer carried out experimental work on negative and positive feedback, and published his results in 1932 and 1934[1,3,4]. It is of interest to note that they agree substantially with the well-known work of Dr. H. S. Black. The writer gave some practical examples showing the great improvement produced by the use of negative feedback ; for instance, for a given tuned circuit if the feedback in the positive feedback circuit of Fig. 1 and the bridge circuit, are adjusted in order to get the same stability and the same non-linear distortion, the time constant will be, say, ·0065 seconds for the positive feedback circuit and 2 seconds for the bridge circuit with 50 dbs. negative feedback.

The bridge circuit was produced on commercial basis by "Secla," Ltd., France, in 1932. (Fig. 4.) In this apparatus the negative feedback was variable between 0 and 60 db.

The writer tried also to stabilise oscillator circuits by use of negative feedback[8,9]. He also thought to use resistance-capacity tuning for oscillators[2] and he tried, in collaboration with J. Bernamont, to apply negative feedback to radio circuits[7]. The non-shunted cathode feedback resistor was used with good results.

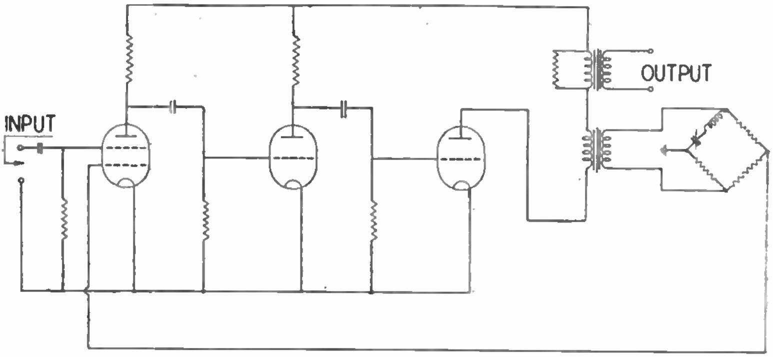

Fig. 4.—Simplified circuit of the negative feedback selective amplifier produced commercially by "Secla," Ltd., Paris, in 1932. The negative feedback was adjustable from 0 to 60 dbs.

2. AN OUTPUT VOLTAGE STABILISER FOR VARIABLE FREQUENCY OSCILLATORS[18]

It is a common practice to adjust the frequency of oscillators by varying the capacity or inductance of the tuned circuit which determines the frequency. It is generally found, however, that without some stabilising means, the amplitude of the oscillation varies sometimes considerably as the frequency is changed.

Some means of stabilisation have already been suggested in the past, such as the use of a diode in shunt on the tuned circuit, but while such arrangements produce some improvement, the stabilisation obtained is insufficient or many purposes.

Fig. 5 represents a tuned circuit, as is commonly associated with a valve to generate oscillations, and the stabilising diode D. The cathode of this diode is biased positively by a battery B or other suitable means, and the biasing voltage is chosen to be slightly less than the desired maximum voltage to be generated in the tuned circuit. If the amplitude of the oscillations should tend to increase when the frequency is changed, the diode D will become conducting for the peaks of the positive half waves and will act as a load on the tuned circuit which increases as the amplitude increases. It therefore tends to limit the amplitude of the oscillations. However, experience shows that the stabilising control is not very great, and considerable amplitude variations still occur. An example is shown in Fig. 6 where the curve A shows the variation of the output voltage of a particular oscillator expressed as a level in decibels referred to an arbitrary zero level when the frequency is varied

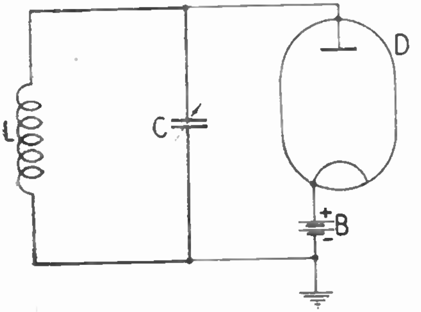

Fig. 5.—Principle of the amplitude stabilisation by diode. LC is the tuned circuit of the oscillator and B a convenient positive bias. This method is not very efficient.

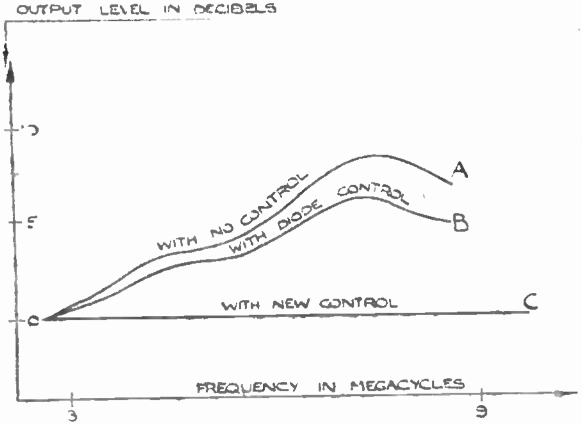

Fig. 6.—Showing the stabilising results which can be obtained with the diode (curve B) and the triode control (curve C).

over a range of 3 to 9 megacycles per second, there being no amplitude limitation. Curve B shows the variation obtained with a simple diode control as just described. The improvement is clearly not very great.

Curve C shows the stability which can be obtained by using an improved limiting device shown diagrammatically in Fig. 7. The effectiveness of the control is greatly increased by using a triode valve V to shunt the tuned circuit instead of a diode, and by applying to the control grid the amplified and rectified variations of the oscillating voltage by means of the detector amplifier DA connected as shown. This can be most easily appreciated in the following way. Let v be a variation in the amplitude of the oscillating voltage. This will be detected and amplified in DA and will be multiplied by some factorμ_1, becoming $\mu_1 v$. This voltage is applied to the grid of the valve V and produces the damping effect on the tuned circuit as another voltage P applied to the plate of valve V and equal to $\mu_1 V$ multiplied by another factor μ_2; thus $P = \mu_1 \mu_2 V$. It is evident that a much greater load will be placed on the tuned circuit for the same value of v with the arrangement of Fig. 7, than with that of Fig. 5, and accordingly a much more effective stabilising control is obtained. Many standard triode valves have an amplification factor μ_2 as high as 50, and μ_1 may easily be made equal to 10. A multiplication of 500 is thus obtained. The result is curve C, Fig. 6, in which the variation over the whole frequency band is less than 0·05 db.

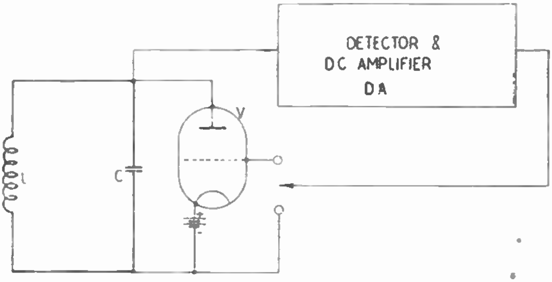

Fig. 7.—A very efficient amplitude stabilising method. The diode of Fig. 5 is replaced by a triode and any variation of the oscillating voltage is detected, amplified and transmitted to the grid of the triode.

Fig. 8 shows a simplified diagram of a practical stabilising circuit. This is generally in accordance with Fig. 7. In this circuit, the variations of the H.F. oscillating voltage are detected by a conveniently biased diode D, and amplified by a direct current amplifier valve V_1.

The cathode of the diode is biased positively by suitable means shown as a battery B_1, the voltage of which should be just slightly less than the minimum amplitude of the uncontrolled oscillating voltage in the tuned circuit, taken over the whole frequency range of interest. The diode will accordingly tend to produce a rectified output voltage in the load resistance, R_{10}, proportioned to the excess amplitude. This voltage is smoothed in the circuit comprising the resistance R_{11} and condenser C_9, and applied to the valve V_1 arranged as a direct current amplifier, producing an amplified continuous voltage across the load resistance R_2 shunted by the by pass condenser C_2 and is applied to the control valve V_2 which then operates as a very sensitive amplitude limiter.

Any increase of the oscillating voltage across the tuned circuit produces an equal negative voltage across condenser C_1 and C_9 and a much greater voltage increase of the grid of valve V_2. This greatly increases the load across the tuned circuit and reduces the oscillating voltage to very nearly its initial value.

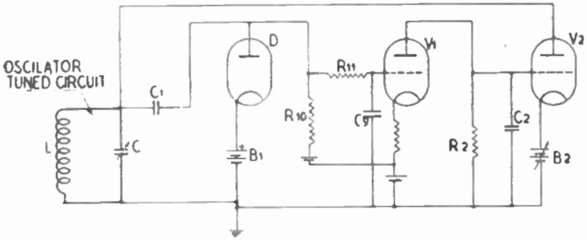

Fig. 8.—Simplified diagram of a stabilising circuit using the triode control method. D is a diode detector, V_1 a D.C. valve amplifier and V_2 the triode control valve.

The cathole of valve V_2 is biased positively by suitable means shown as a battery B_2, the voltage of which should be adjusted in order that the current flows in valve V_2 only during the positive picks of the oscillating voltage. When the adjustment is correct, the oscillating waveform becomes sinusoidal with a very small percentage of harmonics.

Fig. 9 shows the details of an actual practical arrangement with which the method has been tested and with which curve C of Fig. 6 was obtained.

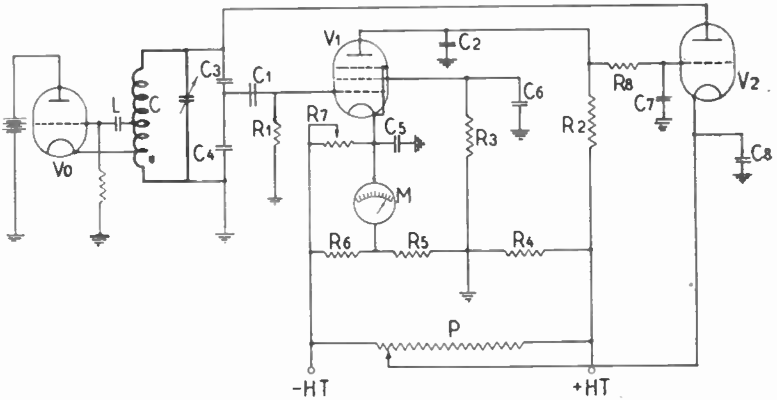

Fig. 9.—A simple stabilising circuit. V_1 is used as detector (grid-cathode part of the valve), valve voltmeter and D C. amplifier. The circuit is designed for use with a multirange oscillator covering the total frequency band :—30 K/cs-9 Mc/s. In each range the output voltage is constant.

R_1 = 10 *Meg.*
R_2 = 0·2 *Meg.*
R_3 = 10,000 *ohms.*
R_4 = 0·1 *Meg.*
R_5 = 15,000 *ohms.*
R_6 = 300 *ohms.*
R_7 = 3,000 *ohms.*
R_8 = 1 *Meg.*
P = 0·2 *Meg.*
C_1 = 100 *p.f.*
C_2 = 500 *p.f.*
C_3 = 5 *p.f.*
C_4 = 100 *p.f.*
C_5 = 0·2 *m.f.*
C_6 = 0·1 *m.f.*
C_7 = 500 *p.f.*
C_8 = 0·1 *m.f.*
V_1 = *6J7G*
V_2 : *6V6G*

This circuit is slightly different from the circuit of Fig. 8. There is no diode, the grid cathode portion of valve V_1 being used as a diode, and there is no battery B_1. Only a small fraction of the oscillating voltage is transmitted to the grid of valve V_1 by means of the potentiometer divider C_3C_4. The sensitivity is much smaller than with the circuit of Fig. 8 but is still sufficient to give a perfect stabilisation. Valve V_1 is used also as a valve voltmeter, and the oscillating voltage across C_4 is read on the meter M.

Adjustment for the best control is easy. The bias of the cathode of valve V_2 should be adjusted by means of the potentiometer P until maximum stabilisation is obtained. It will be clear that if the cathode should be given a positive potential greater than the maximum oscillating peak voltage there will be no control at all as the valve will always have an infinite impedance. By making the cathode progressively more negative the control increases until some point is reached at which the load on the tuned circuit, at the positive picks, becomes so great that the control is maximum and the amplitude of the oscillating voltage start to decrease rapidly. The best operation point will be just before this occurs. With the circuit as described and as adjusted in the manner just explained, it is possible to maintain the oscillating voltage constant within about 1 per cent. when it would vary by perhaps 200 per cent. without any control.

The circuit of Fig. 9 has been tried with five different coils in order to cover the frequency band 30 K.C. to 9 M.C., and for each coil the stabilisation was found perfect.

Although the control circuit employs two or three valves, the power necessary for operating them can actually be made small compared with the power necessary for the oscillator valve. For example, valve V_1 could be a very low power valve whose maximum current is not more than, say, 2 milliamperes ; and the valve V_2 owing to the manner in which it operates will generally draw a plate current of less than 1 milliampere, even if a power output valve such as a 6V6 or a 6L6 is used. The potential divider arrangement can also be arranged so that the total current drain is not more than about 7 milliamperes.

4. A METER CONTROL UNIT—CONSTANT OUTPUT CURRENT OSCILLATOR[14]

The meter control unit which will now be described has been created in order to stabilise the output current produced by a high frequency oscillator. It has many other stabilising applications and, for this reason, it will be described first independently of any application.

Fig. 10 shows a schematic circuit diagram of the meter control unit. It comprises a high frequency oscillator whose tuned circuit produces a strong field, a detector tuned on the oscillator and two coupling coils connected in series and fixed on the needle of the meter.

The oscillator and the detector are shielded so that no direct transmission is possible. However, just in front of the oscillator coil and in front of the detector coil a hole in the shield has been made. The oscillator radiates a strong field outside across the first hole, but only a negligible fraction enters the detector shield across the second hole. The coupling between oscillator and detector is produced by the two coupling coils fixed on the needle or the meter. The system is so arranged that this coupling is negligible for all positions of the needle except one and the adjacent points.

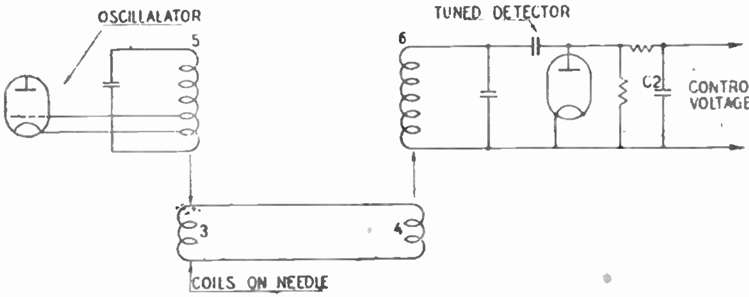

Fig. 10.—Principle of the meter control unit. The oscillator coil 5 is coupled to the detector coil 6 by means of the series coils 3 and 4 fixed on the needle. When the needle moves the coupling varies.

This arrangement is shown in Figs. 11 and 12.

Fig. 11 shows the respective positions of the oscillator, the detector and the two coupling coils with relation to the needle of the meter and its pivot. The coupling is maximum when the needle is in front of point M on the meter scale.

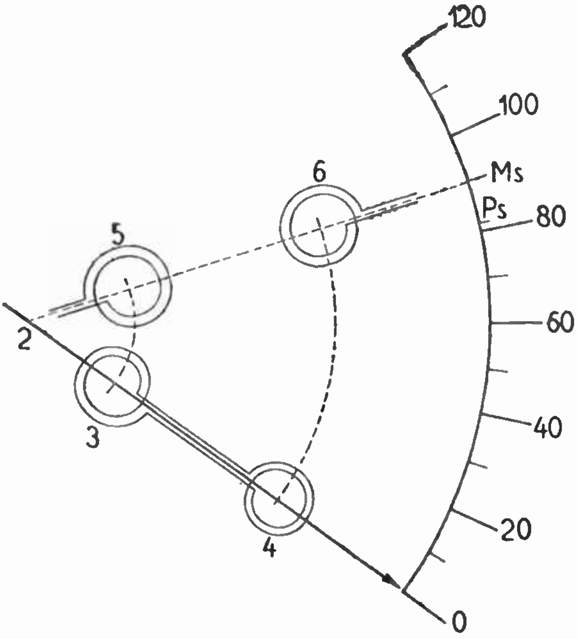

Fig. 11 — Relative position of the oscillator, detector and coupling coils. The coupling is negligible from 0 to point P_s on the scale and maximum when the needle is opposite point M_s.

Fig. 12 is a diagram giving an elevation of the arrangement of Fig. 11 showing how the coils are placed when the needle is opposite point M_s on the scale. The meter is of the moving coil type having a horizontal movement and a vertical scale. The coupling coils are edgewise on the needle and are immediately below the oscillator and detector coils. The oscillator and detector coils are mounted opposite corresponding circular holes in a metal screen.

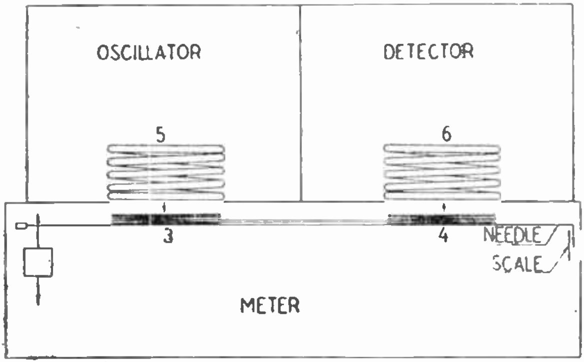

Fig. 12. — Relative position of the oscillator, detector an meter. The screening is such that the direct coupling between oscillator and detector is negligible.

The coupling coils must be very light in order that the movement of the needle system shall not be appreciably affected and may be fixed to the needle by any suitable cement. Mr. M. L. Gayford suggested that coils of the type used in " Western Electric " and " Standard Telephones and Cables " microphones and loudspeakers are specially suitable for this purpose. Such coils are constructed from very thin aluminium ribbon wound edgewise to form a thin self-supporting hollow cylinder. Two coils of this type were fixed on the needle of a 100 microamperes full-scale deflection meter by means of a convenient cement, and it was found that the depression of the needle produced by the added weight of the coils was so small that it was unnecessary to rebalance the moving system.

In order to obtain the best results the detector and the coupling coils should be tuned to the oscillator frequency. This is quite easy in the case of the detector coil which can easily be shunted by an appropriate tuning condenser ; but it is impracticable to add anything to the coupling coils. However, when constructed in the manner just described, they have a relatively high self capacity and it has been found that with a dozen turns the coupling coils are self-resonant at a frequency of a few megacycles. The frequency of the oscillator is therefore chosen accordingly and the detector coil is also tuned to this frequency.

Referring again to Fig. 11, when the needle is on the zero graduation as shown, there will be no appreciable coupling between the oscillator or the detector coils and their corresponding coupling coils. There will be, therefore, no appreciable control voltage at the detector output. As, however, the needle approaches point M_s, a small voltage will be obtained and this increases to a sharp maximum when the needle reaches this graduation, and then decreases very rapidly as the needle travels farther. This is shown by the curve of Fig. 13. It will be seen that a sharp maximum of more than 20 volts is obtained.

It is obvious that this unit can be used whenever it is required to get a constant deflection on the meter. The detector will give a control voltage which can be used in a convenient A.V.C. circuit. The writer has used this unit to control the high frequency current circulating in a coil L_1 coupled

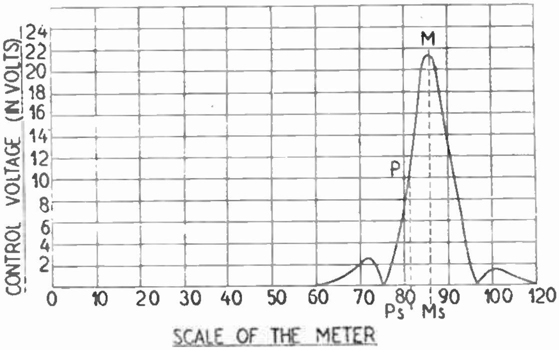

Fig. 13.—*Control voltage curve obtained with the meter control unit represented in Figs.* 13 *to* 15. *When used conveniently in an A.V.C. circuit, the needle will stop in front of point Ps on the scale, or a point near Ps.*

with the tuned circuit of a Hartley oscillator (Fig. 14) in a Q meter circuit. This current was measured by a high frequency thermocouple connected to a microammeter. The current varies so much when the frequency of the oscillator is changed that unless great care is taken, the thermocouple blows off. With the meter control unit replacing the micrometer and with the control circuit of Fig. 17 the current was controlled effectively. The needle

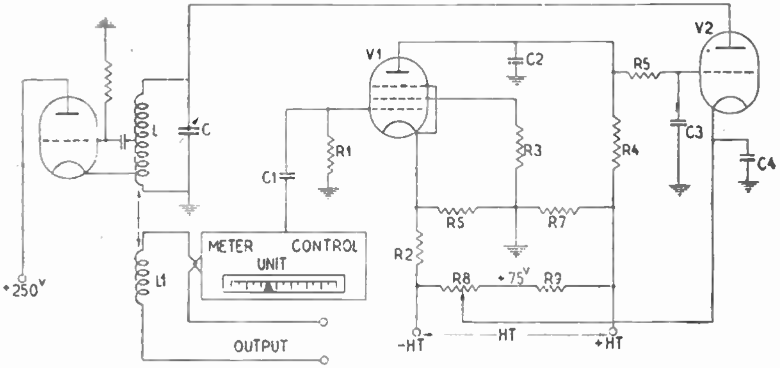

Fig. 14.—*A Q meter circuit giving a constant H.F. current output. The H.F. current is measured by a thermocouple connected to the meter of the control unit.* 100 *per cent. variation in current is reduced to less than* 3 *per cent.*

used to stop and stay at about division 80 corresponding to point P of the control curve Fig. 16, with a maximum deviation of 3 per cent., for a variation of more than 100 per cent. without any control.

M. M. LEVY

PART II

SOME PROBLEMS CONCERNING INSTABILITIES PRODUCED BY MAINS VOLTAGE VARIATIONS

SUMMARY

Some simple methods of stabilisation and examples of application are described.

1. METHOD OF TOTAL COMPENSATION

The effects produced on a circuit by mains variations can be approximately compensated by rectifying the mains variations and applying the voltage thus obtained on the grids of some valves of the circuit. A very simple control circuit is described.

2. METHOD OF INDIVIDUAL COMPENSATION

For each valve a convenient fraction of the H.T. supply voltage is applied on the cathode, so that the cathode current becomes independent of H.T. voltage variations.

The simplicity of the method is shown by two examples : a stabilised selective amplifier and a stabilised valve voltmeter circuit. In this latter case, the anode supply voltage could be changed from 220 to 300 volts (± 15 per cent.) without any detectable change in the zero setting or in the calibration of the valve voltmeter.

3. METHOD OF COMPENSATION FOR NON-LINEAR ELEMENTS

The anode current of a valve is not proportional to the anode-cathode voltage. When the anode-cathode impedance of a valve is in a bridge circuit, the balance of the bridge varies with the H.T. supply voltage. To obtain a balance independent of the H.T. voltage a circuit simulating the anode-cathode impedance must be used in place of one resistance of the bridge. Some circuits using neon tubes are described and two valve voltmeter circuits are given as examples of application. The zero setting in these circuits is not affected by ± 20 per cent. voltage variations of the H.T. supply.

4. A SIMPLE H.T. STABILISER CIRCUIT FOR PENTODE VALVES

In the case of pentode valves the anode current is practically independent of the anode voltage. Thus, a very good control can be obtained by stabilising the screen voltage only. As the screen load is small compared to the anode load, this method is very economical.

A simple stabiliser circuit is described, and some applications are given. In one example, a variation of ± 15 per cent. of the H.T. voltage produces no visible variation of the anode current of two power pentodes, although the load taken by the stabiliser is only some per cent. of the total load.

1. METHOD OF TOTAL COMPENSATION

Fig. 15 shows in block schematic form the principle of the method. A load circuit, which may be an amplifier, oscillator, modulator or any other type of electronic circuit, is supplied from a supply transformer PT through a power rectifier unit. The voltage of the main supply will usually be subject to variations from time to time which may quite commonly reach ± 10 per cent., and generally such variations cause corresponding variations in the characteristics or performance of the load circuit. For example, if this circuit is an amplifier, the gain will usually increase or decrease when the supply voltage increases or decreases, the relation being approximately linear for moderate variations of the supply voltage. Similarly if the load circuit is an oscillator, the frequency and the output current or voltage may vary in a similar sort of way.

To compensate for the effect of these variations, a D.C. control voltage, varying in accordance with the main supply voltage variations, is derived from the mains transformer by means of a control unit and applied to the load unit in such a manner as to counteract the changes produced by the mains supply variations. A simple method is to apply the control voltage to a grid of one or more of the valves in the load circuit. In this case it is necessary to arrange so that the control voltage varies in opposite sense to the mains supply voltage.

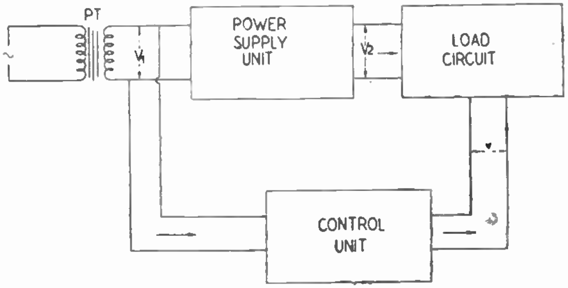

Fig. 15.—Principle of the method of compensation. The fluctuations of the mains voltage V_1 are detected and used as a control voltage v applied conveniently in the load circuit in order to compensate the effects produced by the variations of the H.T. voltage V_2.

This can be done very easily with the diode detector circuit of Fig. 16. A diode D has the cathode connected to earth through a neon tube N and to the positive terminal of the high tension supply through a resistance R_3. The cathode accordingly assumes a fixed positive potential V_3 determined

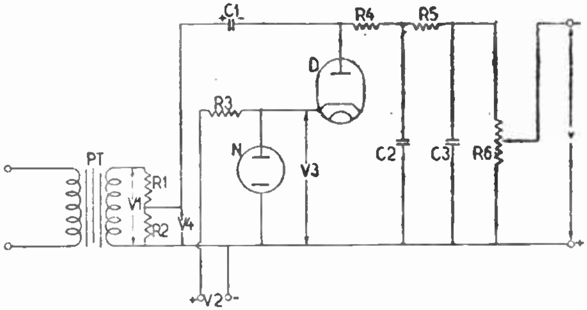

Fig. 16.—A simple control circuit. The fluctuations of voltage V_4 are detected by diode D and smoothing circuit R_4 C_2, R_5 C_3. For maximum sensitivity the cathode of diode D is positively biased by a small neon tube N and a convenient fraction V_4 of the mains voltage V_1 is applied on the diode.

Diode valve : Mullard EA50. Neon valve : S.T.C. Type VLS.405.

V_1 = 400 ± 40 *volts A.C.*
V_2 = 250 ± 25 *volts D.C.*
V_3 = 70 *volts D.C.*
V_4 = 80 *volts* ± 8 *volts D.C.*
V = −1 *to* −9 *volts D.C.*

R_1 = 1 *megohm*
R_2 = 0·2 *megohm*
R_3 = 1 *megohm*
R_4 = 0·5 *megohm*
R_5 = 0·5 *megohm*
R_6 = 1 *megohm*

C_1 = 0·01 *mfd.*
C_2 = 2 *mfd.*
C_3 = 2 *mfd.*

by the neon tube N, which potential is independent of the variations of V_2. The anode of the diode is connected through a condenser C_1 to a tapping point on a resistance potentiometer formed by the resistances R_1 and R_2 connected in series across the mains transformer (Fig. 16), so that an alternating voltage V_4, which is a known fraction of V_1, is applied through the condenser C_1 to the anode of the diode.

The load on the diode D comprises the series connected resistances R_4, R_5 and R_6, the condensers C_2 and C_3 being provided for smoothing purposes. The resistance R_6 is provided with an adjustable tap from which an appropriate control voltage v may be obtained for application to the load circuit.

The action of the circuit will be understood from the diagram shown in Fig. 17. The curve A indicates the alternating voltage applied to the diode ; the line V_4 represents the maximum positive amplitude of A, and is supposed to vary between the limits V_4 max. and V_4 min. The cathode voltage V_3 is represented by the chain dotted line, and should be chosen to be a little less than V_4 min.

When the instantaneous positive voltage of the curve A exceeds the value V_3, the Condenser C_1 charges through the diode in such a manner as to reduce the anode potential so that it becomes negative to the cathode. If the capacity of the condenser C_1 and the total negative resistance $R_4 + R_5 + R_6$ be chosen so that the time constant of the circuit is large compared with the period of the alternating current supply, the condenser will not be able to discharge appreciably between the successive positive loops of the curve A. The condenser C_1 will accordingly acquire a difference of potential substantially equal to $V_4 - V_3$, and the terminal connected to the anode will be negative ; and it is from this difference of potential that the control voltage v is derived by smoothing across R_4, C_2 and R_5, C_3.

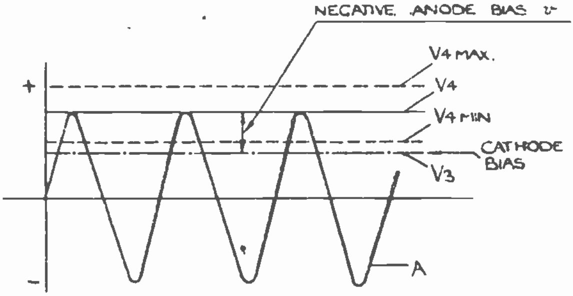

Fig. 17.—Diagram explaining the working principle of the control circuit of The voltage V_4 fluctuates between V_4 min. and V_4 max. The neon tube N biases the cathode at voltage V_3. Thus, the voltage acting on the diode is $V_4 - V_3$. The detected voltage v is used as control voltage.

Numerical values for the components corresponding to a very common case are given in Fig. 16. In this case the alternating voltage V_1 was 280 volts r.m.s., the peak amplitude being therefore about 400 volts. The variation of the supply was ± 10 per cent. The high tension voltage V_2 derived from V_1 in the power unit was 250 volts ± 10 per cent.

The neon tube produced a constant voltage difference of 70 volts and the current flowing through it was about 180 microamperes. The diode D was a Mullard EA50, small television diode. The current flowing through it was negligible. The maximum amplitude V_4 is 80 ± 8 volts so that the potential acquired by the condenser C_1 varies from -18 to -2 volts, and the maximum available value for the control voltage v varies from -9 to -1 volts.

The load on the power supply is negligible: the current taken from the transformer PT is less than 300 microamperes (r.m.s.) and that taken from the high tension supply at V_2 is less than 300 microamperes.

2. METHOD OF INDIVIDUAL COMPENSATION

H.T. voltage variations can be compensated in each valve by applying in the cathode circuit a convenient fraction of the H.T. voltage.

Fig. 18a shows in its simplest form a single valve stage. The voltage of the anode supply source is supposed to be variable and this is indicated by the electromotive force E_a shown in series with the + H.T. terminal and intended to represent a voltage variation. If μ is the amplification factor of the valve, then it is well known that the electromotive force E_a in the anode circuit is equivalent to an electromotive force $-E_a/\mu$ applied in the control grid circuit or an electromotive force E_a/μ applied in the cathode circuit. If, therefore, an electromotive force E_a/μ is effectively applied to

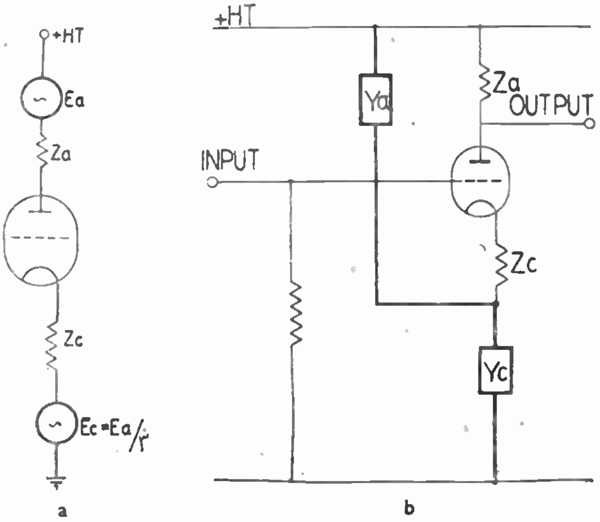

Fig. 18.—Principle of the method of neutralising H.T. voltage fluctuations.

(*a*) *An e.m.f.* E_a *in the anode circuit is exactly balanced by an e.m.f.* $E_c = E_a/\mu$ *in the cathode circuit (*μ *being the amplification factor of the valve) and no current will be produced by these e.m.f.*

(*b*) *A fraction* $1/\mu$ *of the H.T. voltage is applied to the cathode of the valve by means of the impedances* Y_a *and* Y_c. *H.T. voltage fluctuations will have no effect on the anode current of the valve if* $Y_c = \frac{Y_a + Y_c}{\mu}$

Practical examples are given in Figs. 19 and 20.

the cathode the change in anode current produced by the variation E_a will be exactly counterbalanced by the change caused by the voltage applied to the cathode, so that the anode current will be rendered independent of the variations of the anode supply source, and the performance of the valve will be substantially unaffected.

Fig. 18b shows how this requirement may be carried out. An impedance Y_c is connected in series with the cathode impedance Z_c as shown, and the junction point of Y_c and Z_c is connected through another impedance Y_a to the + H.T. The impedances Y_a and Y_c are then chosen so that $\frac{Y_a + Y_c}{Y_c} = \mu$ or $Y_a/Y_c = \mu - 1$. Under these conditions a varying electromotive force of $+ E_a/\mu$ will be effectively applied to the cathode, which is the conditions desired to neutralise the effect of E_a in the ande circuit.

The impedances Y_a and Y_c can take any desired form, depending on the conditions which have to be met. In the simplest case they will both be pure resistances. If the cathode resistance is shunted by a capacity, Y_a must be also a resistance shunted by a capacity. However, for most applications only very slow variations occur so that one can neglect the shunting capacity and use only a resistance.

The total D.C. voltage applied to the cathode by the impedance Y_c will be $+ E/\mu$ where E is the voltage of the anode supply source. This will in many cases effectively apply to the control grid a negative bias which is too great accordingly the grid must be biassed positively. This can be done very easily with a small neon tube as shown in Fig. 19.

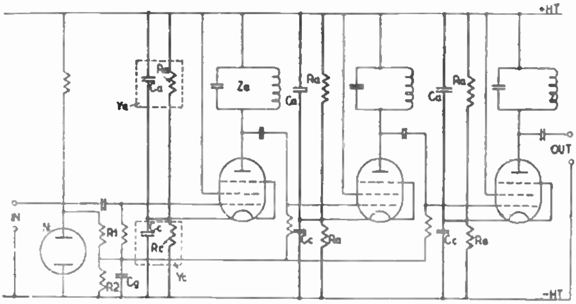

Fig. 19.—Example of neutralised selective amplifier. $R_a = R_c\ (\mu - 1)$ *and* $C_a = C_c/(\mu - 1)$. *The grids are biassed conveniently by a neon tube N. Condensers* C_a *can be neglected for very slow fluctuations.*

Fig. 19 shows a practical example of a selective amplifier neutralised for variations of the anode voltage. The amplifier has three stages and each stage is neutralised by a resistance R_a shunted or not by a capacity C_a. The condition expressed above becomes here:

$$R_a = (\mu - 1)\,R_c$$
$$C_a = C_c/(\mu - 1)$$

The neon tube N supplies the counteracting bias for all the control grids. As all the valves are supposed to be similar, the control grids can all be connected to the same point of the potential divider shunted across the neon tube N.

Fig. 20 shows a valve voltmeter circuit to which the neutralising principle is applied. D is a diode detector, V a D.C. valve amplifier, N_1 the biassing neon valve and N_2 a neon valve used to balance the drop of voltage across R_3 in order to get a zero deflection on the meter M, in the absence of signal. Care must be taken to use a stable neon tube N_2.

The valve V being neutralised, the plate current is practically independent of the H.T. voltage. Thus the zero adjustment and the calibration are not affected by H.T. voltage variations.

With the arrangement of Fig. 20 and the values indicated for the components, a full scale deflection of the meter was produced when 0·45 volts alternating current was applied at the input. It was found that the anode supply voltage could be changed from 220 to 300 volts without any detectable change in the zero setting or in the calibration of the valve voltmeter.

The same circuit without the stabilising resistance R_a gives a variation of 150 microamps (75 per cent. of full scale) for a variation of the H.T. voltage of 20 volts only.

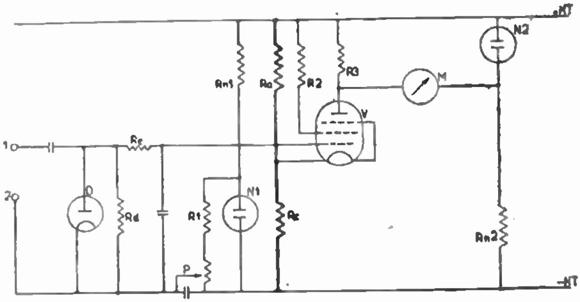

Fig. 20.—*Example of neutralised valve voltmeter circuit. This makes the calibration and the zero setting independent of the H.T. voltage within the practical limits* 200-300 *volts.*

*Valve V : Mullard Pentode EF.*50.

*Diode D : Mullard EA.*50.
Neon Tubes N_1 *and* N_2 *: S.T.C. type VLS.*405.

Meter : 200 *microamperes full scale.*

$R_1 = 0{\cdot}6$ *megohm*
$R_2 = 0{\cdot}02$ *megohm*
$R_3 = 0{\cdot}026$ *megohm*
$R_a = 0{\cdot}067$ *megohm*
$R_c = 1{,}000$ *ohms.*

$R_d = 10$ *megohms*
$R_e = 2$ *megohms*
$R_{n1} = 0{\cdot}3$ *megohms*
$R_{n2} = 0{\cdot}25$ *megohms*

Sensitivity : Full scale deflection for 0·54 *volts.*

Stability : No visible movement of the needle when the H.T. voltage varies from 220 *volts to* 300 *volts.*

Calibration : No Visible variation within the same limits.

3. METHOD OF COMPENSATION FOR NON-LINEAR ELEMENTS—APPLICATION TO VOLTMETER CIRCUITS

Fig. 21 shows in its simplest form the circuit of a commonly used thermionic valve voltmeter. It is a wheatstone bridge in which one resistance is replaced by the anode cathode impedance of a valve. One of the resistances is made adjustable so that when the voltage applied to the control grid is zero the bridge may be balanced and the meter reads zero. When a voltage to be measured is applied to the control grid, the anode-cathode impedance of the valve is changed and the condition of balance of the bridge is altered, so that the meter gives a reading which depends on the applied voltage. It is found, however, that if the voltage of the anode supply changes, the condition of balance of the bridge is altered and a large zero error often results. Changes in zero are also produced by variations in the cathode heating source, but the changes are slow and of negligible importance, so that a good practical improvement can be obtained in considering only the variations of the anode supply source.

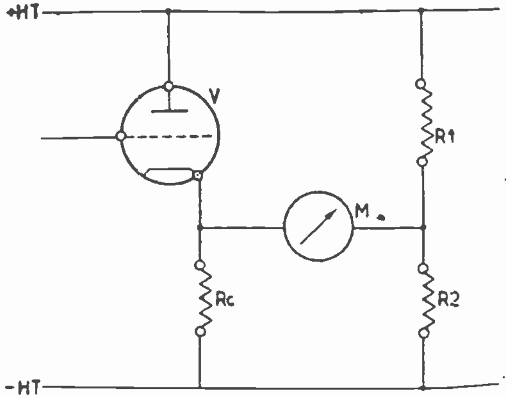

Fig. 21.—Usual bridge circuit for valve voltmeters. H.T. voltage fluctuations are not balanced because the anode-cathode current in the valve is not proportional to the voltage applied across it.

And these variations are important. To give an idea of their magnitude, in a particular valve voltmeter, it was found that a 10 per cent. change in the anode supply voltage produced a change of zero of the order of a quarter of the total range of the indicating instrument. This is due to the fact that the anode current is not proportional to the anode-cathode voltage. According to the grid bias value, the anode current can vary proportionately more or less than the anode voltage. To get a zero balance independent of the H.T. voltage value, one of the resistances of the bridge must be replaced by an impedance simulating the anode-cathode impedance of the valve.

This can be done very simply by using a second valve identical to the first. However, there is another more economical solution. Referring again to Fig. 21, it is proposed to get in resistance R_2 a current varying proportionately to the current circulating in R_c. If R_2 is fed across R_1 (Fig. 22a) this result will not be obtained as the current will then vary proportionately to the H.T. voltage and not to the current circulating in R_c. However, if the circuit of Fig. 22b is used, the current in R_2 will vary more quickly than the H.T. voltage; and if the circuit of Fig. 22c is used, the current will vary more slowly than the H.T. voltage. This can be seen easily if the variable resistance R_a is reduced to zero in each of these figures. If, now, this resistance is increased considerably, the current will become again proportional to the H.T. voltage. Thus, one of these two circuits with a convenient adjustment of R_a will produce the required current in R_2.

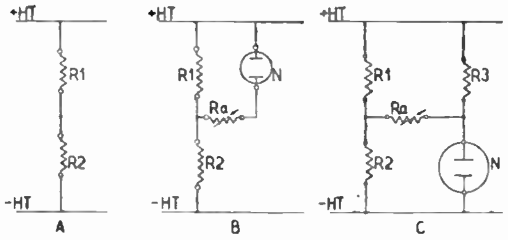

Fig. 22.—Circuits giving in R_2 a current varying in the following ways :

(a) *Proportionately to the H.T. voltage.*

(b) *Quicker than the H.T. voltage.*

(c) *Slower than the H.T. voltage.*

By varying R_a the slope of the voltage-current characteristic can be varied.

Fig. 23 represents a valve voltmeter circuit in which the stabilising circuit of Fig. 22 is used. With this circuit and the values of the components indicated, a full scale deflection on the meter was produced when a voltage of — 0·25 volts was applied to the control grid and the variation of zero was 0·3 micro-amperes for a variation of ± 50 volts of the H.T. voltage, the average value being 250 volts.

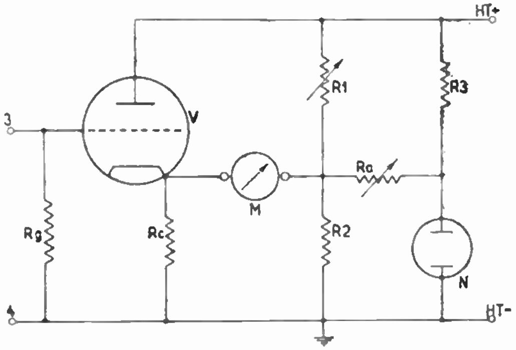

Fig. 23.—Bridge circuit of Fig. 7 combined with balancing circuit of Fig. 8c. The zero setting is independent of H.T. variations.

Rheostat R_1 : Balance adjustment.

Rheostat R_a : Zero adjustment.

Fig. 24 shows a valve voltmeter using a diode detector. It was found necessary and convenient to use the stabilising circuit of Fig. 22. With this arrangement a full scale deflection of the meter was obtained by the application of an alternating voltage of 0·6 volts and the zero stability obtained was about ± 1 microamperes when the H.T. voltage was varied ± 50 volts from 250 volts. The same voltage variation was found to produce only a 2 per cent. variation of sensitivity at full scale deflection. The stability of the calibration is principally due to the high negative feedback produced by the resistances R_2 and R_c which have been given for this reason larger values than previously.

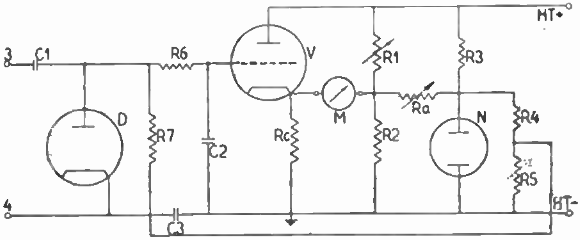

Fig. 24.—Diode detector combined with bridge circuit of Fig. 7 and balancing circuit of Fig. 8c.

Diode : Mullard EA.50.

Triode : Type 75.

Neon Tube : STC type VLS.405.

Meter : 200 microamperes full scale.

R_1 = 0·23 *megohms*
R_2 = 2,000 *ohms*
R_3 = 70,000 *ohms*
R_4 = 1 *megohm*
R_5 = 0·1 *megohm*
R_6 = 2 *megohms*
R_7 = 10 *megohms*
R_a = 27,000 *ohms*

Sensitivity : Full scale deflection for ·6 volts applied on the diode.

Zero Stability : Deflection of less than 1 per cent. of full scale when the H.T. voltage varies from 200 to 300 volts.

Calibration : Less than 2 per cent. variation at full scale when the H.T. voltage varies from 200 to 300 volts.

4. A SIMPLE H.T. STABILISER CIRCUIT FOR PENTODE VALVES

The usual electronic stabiliser circuits usually increase greatly the load on the high tension supply source and are for some applications very uneconomical. In these cases, and particularly when it is intended to supply pentode valves, a simple stabilising circuit can be used.

For a pentode valve the plate current is practically independent of the anode voltage but varies appreciably with the voltage applied on the screen. Take, for example, a power pentode such as the 25L6 (4 watts output power, 55 milliamperes plate current, 9 milliamperes slope). The same variation of anode current can be produced either by

1 volt applied on the grid
or 5·5 volt applied on the screen
or 160 volt applied on the anode

The same fact is represented graphically in Fig. 25. It can be seen that if the voltage variation is applied on the screen, it produces 34 times more anode current variation. It is interesting to notice that curve c represents the anode current variation which occurs in usual amplifier circuits using this type of valve. It can be seen that a variation of ± 10 per cent. of the H.T. voltage produces a variation of ± 5 milliamperes or ± 10 per cent. of the anode current.

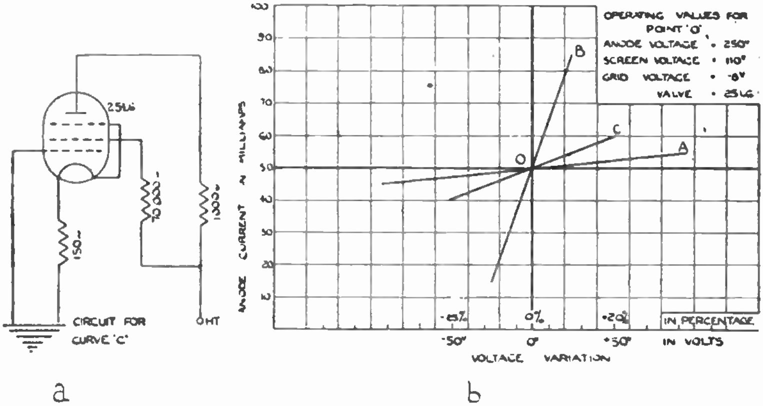

Fig. 25.—Characteristics of a pentode 26L6 showing how the anode current varies when the anode, the screen or the H.T. voltage varies.

Curve A : Anode voltage variable.

Curve B : Screen voltage variable.

Curve C : H.T. voltage variable for circuit of Fig. 25a.

Stabilising the screen voltage is 34 times more effective than stabilising the anode voltage.

Thus, if the screen voltage is stabilised, the anode current will be practically independent of H.T. variations, and if the screen voltage varies in the opposite way to the H.T. voltage a perfect stabilisation can be obtained. By this method, the difficulty is reduced as it is no more necessary to stabilise the great anode load but only the screen load which is a small fraction of the anode load.

A convenient stabiliser circuit is represented in Fig. 26. V_0 is the stabiliser valve and V_1 and V_2 are the load pentode valves. The H.T. voltage variations are transmitted by means of the neon tubes N_1, N_2, N_3 to the grid of the stabiliser valve. This voltage appears across the cathode resistance R_C and, in opposite sign, across resistance R_D. By convenient adjustment of the value of R_D the voltage on the anode can be perfectly stabilised. This anode feeds the screen of the load valves.

With the circuit of Fig. 26 and the values represented, it has been observed that a variation of the H.T. voltage from 220 volts to 310 volts (± 15 per cent.) produces no visible variation of the anode current of the two power pentodes. When the H.T. voltage is increased within the above limits, the screen voltage of the load valves decreases from 108 volts to 107 volts (1 volt variation only).

The adjustment of R_D is not critical and practically independent of the characteristics of the stabilising valve because of the great negative feedback produced by the cathode resistance R_c. In the circuit of Fig. 26 the stabilising valve is an EF.50. As the slope of this valve is 6,500 micro-ohms, and as $R_c = 5{,}000$ ohms, the stabilising feedback factor is

$$\frac{1}{1 + gR_c} = \frac{1}{1 + 32\cdot5} = 3 \text{ per cent.}$$

This means that any change of the characteristics of the valve will be reduced to 3 per cent. of its original value. Thus a change of valve does not affect the adjustments.

The stabilising valve works with a cathode current of 7 milliamperes and the stabilisation is still good with 3 25L6 as load valves. This means that the stabilising valve takes only 4 per cent. of the total load.

In order to appreciate the practical use of this stabiliser circuit, we have measured the anode current variation of a 25L6 valve when the filament voltage is varied ± 10 per cent. This variation has been found equal to ± 1 per cent. so that in many cases there is no need to stabilise the heater supply voltage.

The circuit can also be used as H.T. stabiliser when pentodes are not used if the H.T. current is small. This is the case, for instance, of valve

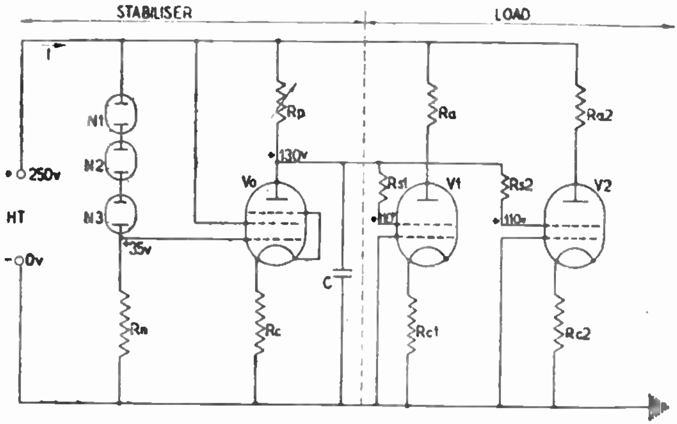

Fig. 26.—A simple stabiliser circuit combined with two pentode load valves.

Stabiliser valve : Mullard EF.50.

Load valves : Pentodes 25L6.

Neon tubes : S.T.C. type VLS.405.

$R_{a1} = R_{a2} = 1{,}000$ *ohms.*
$R_{c1} = R_{c2} = 150$ *ohms.*
$R_c = 5{,}000$ *ohms.*
$R_n = 0\cdot1$ *megohms.*
$R_p = 10{,}000$ *ohms.*
$R_{s1} = R_{s2} = 10{,}000$ *ohms.*
$I = 120$ *milliamperes.*

Stabiliser overload : Less than 6 per cent. of the total load.

Stability : No visible variation of the anode current of the load valves when the H.T. voltages varies from 220 to 310 volts.

voltmeter circuits where the H.T. current is of the order of some milliamperes only.

ACKNOWLEDGMENTS

The author wishes to acknowledge the helpful suggestions and very valuable interest given to this work by Mr. R. Webb who also kindly presented this work to a meeting of the Institution.

DISCUSSION

Mr. H. Tyrrell-Gramann (Associate): Can Mr. Levy give any comparative figures for some of his stabilising circuits used in conjunction with oscillators, as against oscillators using dynatron valves as the oscillator and controlled by a diode?

Regarding suitable circuits to be used for stabilising the screen voltages of large power valves, the Osram KT66 in class AB requires 400 volts on the anode and 250 volts on the screen. The screen current varies by as much as 11 ma. (for two valves) between no load and full load. One method employed uses a potentiometer across the H.T. line to supply the screen voltage, but this potentiometer consumes considerable power if a voltage fluctuation on the screens is to be avoided. I believe Dr. Partridge used a method for stabilising this screen voltage by means of a control valve. Does Mr. Levy recommend any particular type of stabilising circuit for this purpose which can be considered more practical and economical than the potentiometer method?

Mr. J. A. Sargrove (Member): There is one problem for which stabilising methods are very much needed. It is the problem of measuring small voltages, much smaller than one volt. This is important especially for biological studies. Unfortunately the contact potential and unstabilities in heater and supply voltages makes measurements very difficult. Can Mr. Levy suggest any practical stable circuit?

Mr. G. A. V. Sowter (Member): I am interested to know what improvements in Q value is introduced by the bridge amplifier circuit and, also if stabilisation can be applicable easily to audio-frequency oscillators.

Mr. Moore (Visitor): Has Mr. Levy applied his bridge circuit to the testing of condensers?

Mr. E. Cattanes (Member): Has Mr. Levy developed any circuit suitable for stabilising high voltage (1-50 kV), low current power supplies, such as for cathode ray tubes, including those of the oscillator-generated type?

Mr. Levy's statement that his stabilising circuit applied to an oscillator, because controlling the peak amplitude produces a greater stabilising action and less frequency distortion than the usual methods, which operate on the threshold control principle (viz., at zero amplitude), requires some proof.

Whilst it is admitted from a mechanical analogy of the pendulum motion that peak amplitude control must be more effective than threshold control in maintaining oscillator stability, the fact that the action is effective only when the oscillator is running in grid current would seem to denote that this method is more likely to increase, rather than decrease, as stated, the frequency distortion.

Mr. Huscott (Visitor): The measurement of small voltages can be done very easily by a circuit described by Miller. This circuit is a D.C. amplifier in which unstabilities produced by variations of heater voltage and contact potential are eliminated by using a convenient double triode circuit in place of the first valve.

Mr. G. L. Hamburger (Associate Member) : An interesting problem is the control of power supplies voltages. There is not enough data in current literature.

THE REPLY

Mr. M. M. Levy : This discussion and the questions show how much is still to be done in the technic of stabilisation and how restricted and incomplete is the present paper.

As pointed out by Mr. Cattanes, Mr. Hamburger and Mr. Moore, there is a great number of applications such as high voltage low current power supplies for cathode ray tubes, and oscillator-generated type of power supplies for which suitable stabilising circuits will be very useful. Radio engineers are all the time confronted with problems of stabilisation and the success of their work is very often proportional to the degree of stabilisation they can obtain.

Perhaps one of the greatest successes in this field is the sensitive D.C. amplifier made by S. E. Miller (*Electronics*, September, 1941), and described during this dicussion by Mr. Huscott. I believe this circuit is very suitable for the applications which Mr. Sargrove has in view.

Another example of very ingenious stabilising device has been kindly communicated to me by Mr. Tyrrell-Gramann, and is due to Dr. Partridge. It is well known that in power pentode valves the screen voltage is usually lower than the plate voltage. The necessary drop of voltage cannot be obtained by a simple series resistance because the screen current varies with load and the voltage drop would consequently vary in the same proportion. A potentiometer or bleeder resistance can be used but, to keep the screen voltage constant within the close limits required by the manufacturers, the power wasted in the potentiometer has to be so great as to nullify the high efficiency attained in the valve itself. The Partridge control circuit obviates all waste of power in the screen supply and keeps the screen voltage more nearly constant than with usual methods. As shown on the circuit, the screens are supplied with current through an ordinary triode valve. The anode of this valve is connected to the main source of H.T. (point A) and the cathode to the screens which are to be supplied with varying current at a

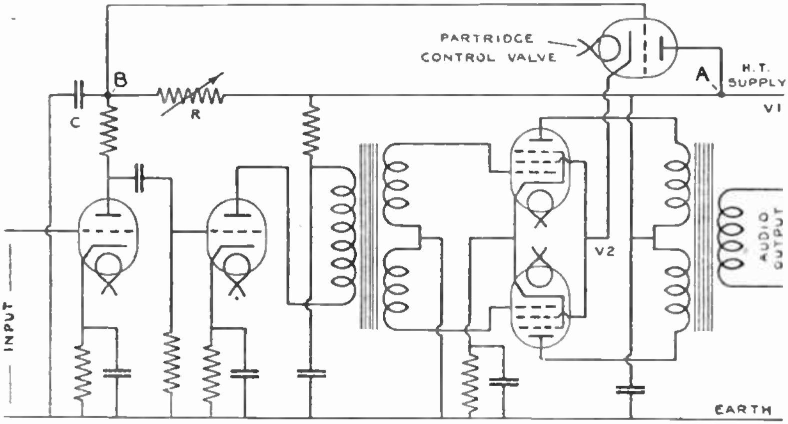

Fig. 27. *The Partridge Control Circuit* constant voltage V2. The grid of the valve is maintained at the same potential V2 as it is desired to keep the said screens. This can be done very conveniently by connecting the grid to a point B in the H.T. supply to the earlier stages of the amplifier that can be adjusted to the required voltage V2 by means of a variable decoupling resistance R. The change of voltage of the screens as the current varies will depend upon the mutual conductance of the control valve. If this is 4 m.a. per volt, a change of 8 m.a. in the screen current will result in a drop of only 2 volts, which is negligible, being only about 0·5 per cent. of the total screen voltage. A further advantage is that the control valve also decouples and smooths the screen supply to an extent dependent upon the amplification factor of the valve. I believe this is a very ingenious application of the properties of the cathode follower, and I am indebted to Mr. Tyrrell-Gramann for communicating to me the literature from which the circuit and the above explanation have been extracted.

On the paper itself some very interesting questions have been presented by Mr. Sowter, Mr. Tyrrell-Gramann and Mr. Cattanes.

Mr. Sowter is interested in negative feedback and has inquired on two important points on which details are missing in the paper : improvement of Q produced by feedback and stabilisation of audio oscillators by negative feedback.

The Q of a tuned circuit can be increased very easily by positive feedback. But this increase is accompanied by a proportional amount of instability. Negative feedback, on the contrary, increases the Q without changing the degree of stability if conveniently applied. Take, for instance, the bridge circuit and assume that the bridge is balanced for the resonance frequency. Then, at this frequency the feedback is nil and the stability is the same as if no feedback loop was used. But, outside this frequency, the bridge is no more balanced and negative feedback appears and reduces the sensitivity of the circuit. This is equivalent to increasing the Q of the circuit. Calculation shows that the Q is then multiplied by the amount of negative feedback ; in other words the Q becomes some hundred times greater than without negative feedback. This improvement in Q can be observed very easily if positive feedback is also used in order to be just below the threshold point of oscillation. The selectivity and the time of build-up are then considerable. If a sine wave tuned on the resonance frequency is suddenly applied at the input, the wave at the output will increase slowly. If positive feedback only is used (Fig. 1) the maximum build-up time which it is possible to obtain is of the order of some seconds only. With negative feedback build-up times of about a minute were easily obtained.

The stability of audio oscillators can be greatly increased by negative feedback. The author studied this question in 1943[8, 9]. However, it is very difficult to give definite conclusions when oscillators are concerned because the stability is affected by many other parameters. In general the stability is increased because applying negative feedback is equivalent to increase in the Q of the tuned circuit.

Concerning the amplitude stabilisation of oscillators, Mr. Tyrrell-Gramann enquired about a very important and very interesting point : Is it necessary to develop a new stabilising circuit when a very simple circuit has already been suggested ?

A simple dynatron circuit controlled by a diode has been described by Groszkowski in 1934 (*P.I.R.E.*, p. 145), and earlier, by Arguimbau (*P.I.R.E.*, 1933, p. 14). The negative resistance of a dynatron is a function of the grid bias, so that if the oscillator is working near the threshold, the amplitude of its oscillations can be controlled easily by varying the grid bias. This control can be made automatic by detecting the amplitude of the oscillations by means of a diode and by applying conveniently the detected voltage on the grid of the dynatron valve. The study by Groszkowski shows that this type of control is very efficient from the frequency point of view. The frequency stability of the system was better than 0·01 per mille, while in an ordinary back-coupled triode oscillator with grid leak this frequency variation was between 0·01 and 1 per mille, and in the same oscillator without grid leak the frequency variation was of the order of a few per cent. But Groszkowski gives no data on the amplitude stabilising.

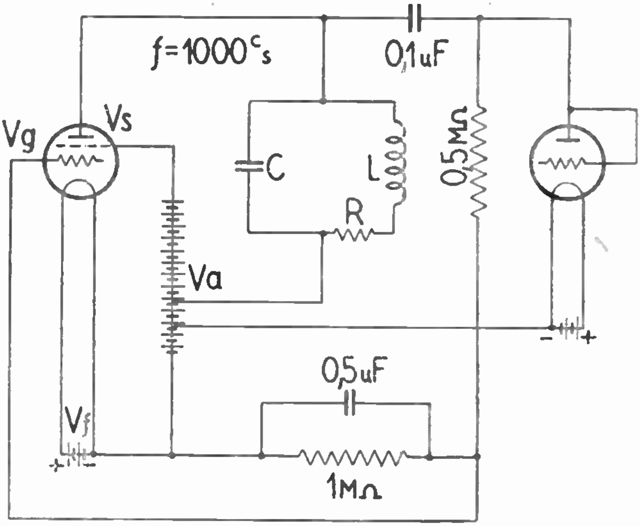

Fig. 28—The Groszkowski Stabilising Circuit.

Other methods of stabilisation have been suggested recently. Except the one mentioned in the paper, all are based on the principle of maintaining the oscillator near the threshold of oscillation by automatic control.

The method mentioned in this paper is based on a very different principle, Instead of working near the threshold of oscillation, I use a grid leak type of oscillator, i.e. an oscillator in which the valve works only during the peaks of oscillation. From one peak to another the oscillation has a tendency to decrease in amplitude because of the damping in the tuned circuit. But this reduction in amplitude is balanced at the second peak by energy produced by the valve and supplied just at this moment.

It is well known that this type of oscillator gives a great frequency stability. Unfortunately the amplitude of oscillation may vary considerably when the frequency of oscillation varies. I have tried to stabilise the amplitude of oscillation by controlling the amount of energy supplied by the valve to the tuned circuit. If the amplitude of oscillation is greater than the valve required, the energy supplied by the valve goes automatically in the control valve (valve V2 in Figs. 8 and 9), and the amplitude of oscillation comes back to the required value.

Mr. Tyrrell-Gramann noticed rightly that the important question is: Which is the best stabilising method? I am not in a position to reply because I have not seen any figures on the amplitude stabilisation of dynatron controlled oscillators.

I would like, in reply to a question by Mr. Cattanes, to point out that in a grid leak oscillator the grid current is very small, because the grid leak may be made very great. Besides, this grid current appears only during the peaks of oscillations and is balanced by the plate or cathode current circulating in the tuned circuit.

I believe in this discussion Mr. Cattanes pointed out a very important question : Is the peak control really better than the threshold control? I was intending to study carefully this question, but routine work did not leave me enough time to do it. I believe this is a very interesting study for a young research worker, and I will be very pleased to receive communication on any study on this subject.

Finally, in reply to a question by Mr. Moore, I must say that the bridge circuit was made for negative feedback studies, although later on it was applied in various other fields. However, we never applied it to the problem interesting Mr. Moore.

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(13) M. LEVY	" Method and circuits for amplitude stabilisation of oscillators." British patent application No. 5114/42, filed 17th April 1942.
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NOTICES

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Obituaries

The General Council regret to record the death of **Wyndham George Williams** (Student), Caerphilly, Glam., whilst on active service.

Wyndham Williams was registered as a Student member of the Institution on October 28th, 1941.

Honours

The Council has tendered congratulations to Edwin C. Buttle (Student) of Norwich, on the occasion of his being awarded the British Empire Medal.

Captain N. H. Blundell (Associate) has been mentioned in despatches for distinguished services in Persia and Iraq during the period February to September, 1943.

Notice of Annual General Meeting

The 19th Annual General Meeting of the Institution will be held on Friday, September 1st, 1944, at 6.15 p.m. in London.

The Agenda of the meeting will be published in the next issue of the Journal.

President Elect 1944-45

Mr. Leslie McMichael (Member) was unanimously nominated President-elect at a meeting of the General Council held on May 5th, 1944.

Founder of the organisation which bears his name and one of the original Founders in 1913 of the Radio Society of Great Britain, Mr. McMichael has been a Vice-President of the Institution for the past three years. In addition to being Chairman of this year's Parliamentary Committee, Mr. Michael has attended meetings of other Committees of the Institution and, if circumstances permit, has expressed his intention of visiting each section of the Institution during the next twelve months.

Election of Council, 1944-45

In accordance with Article 32, the Council will be sending, in June, to each Corporate Member, a list of duly qualified persons nominated by Council for the vacancies about to occur in the office of ordinary members of Council. " After the issue of the Council's list and not later than 21 days after the date of such issue Corporate Members may nominate any other duly qualified person to fill such vacancy by delivering such nomination in writing to the Secretary, together with the written consent of such person to accept office, if elected."

Article 29 provides that half the ordinary members of Council shall retire in rotation, and notice of the six members who will remain on Council for 1944-45 will be circulated to Corporate Members in due course.

Benevolent Fund—Annual General Meeting

The Annual General Meeting of subscribers to the Fund will be held at the offices of the Institution on Friday, September 1st, 1944, at 5 p.m.

The Accounts and an additional list of subscribers (January 1st, 1944-May 31st, 1944) will be circulated to all subscribers in August.

Prisoners of War Fund

Appeals have frequently been made in the Journal for the despatch of textbooks and lesson material in Physics and Mathematics to prisoners of war. Now that the German censorship permits the despatch of radio engineering proper, further opportunity is afforded for helping prisoners of war.

It is of interest to note that with the relaxation of restrictions, the Institution's examinations are now being written by prisoners in several camps. No fees are, of course, imposed by the Institution in connection with the holding of the examinations.

In view of the difficulties of these candidates and other circumstances in procuring suitable study material, the Council of the Institution has approved a recommendation that the Institution should establish a Prisoners of War Fund. The Honorary Treasurer of the Fund is Mr. John Dimmick—Chairman of the Education and Examinations Committee—and members of the Institution are invited to send donations to the Fund. Such contributions will be used solely for the despatch of lesson material and books to prisoners of war.

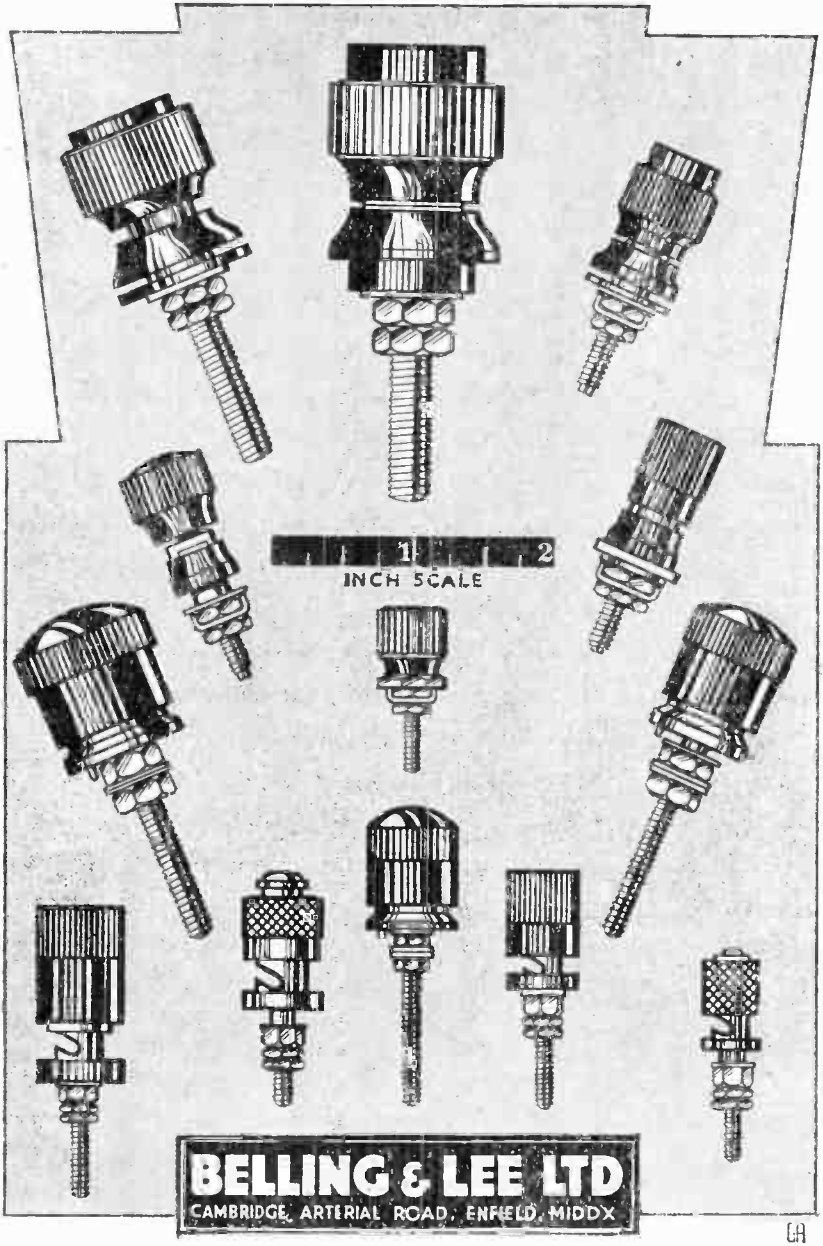
The President has opened the Fund with a very generous donation, and it is hoped that as many members as possible will assist the Committee in this good work.

North-Western Section

It is intended that the North-Western Section shall recommence holding regular monthly meetings as from September, 1944. Hitherto, meetings of the Section have always been held in Manchester, but many members have requested that Liverpool be used as an alternative centre or that a new Section be formed with Liverpool as the venue for meetings. Comments are required from members resident in the areas in question.

Forthcoming Meetings

The session of Section Meetings ends in May of each year and most Sections will recommence their monthly meetings in September. During the interval, it is hoped to recommence the practice of sending to all members notification of the programme of meetings throughout the various Sections.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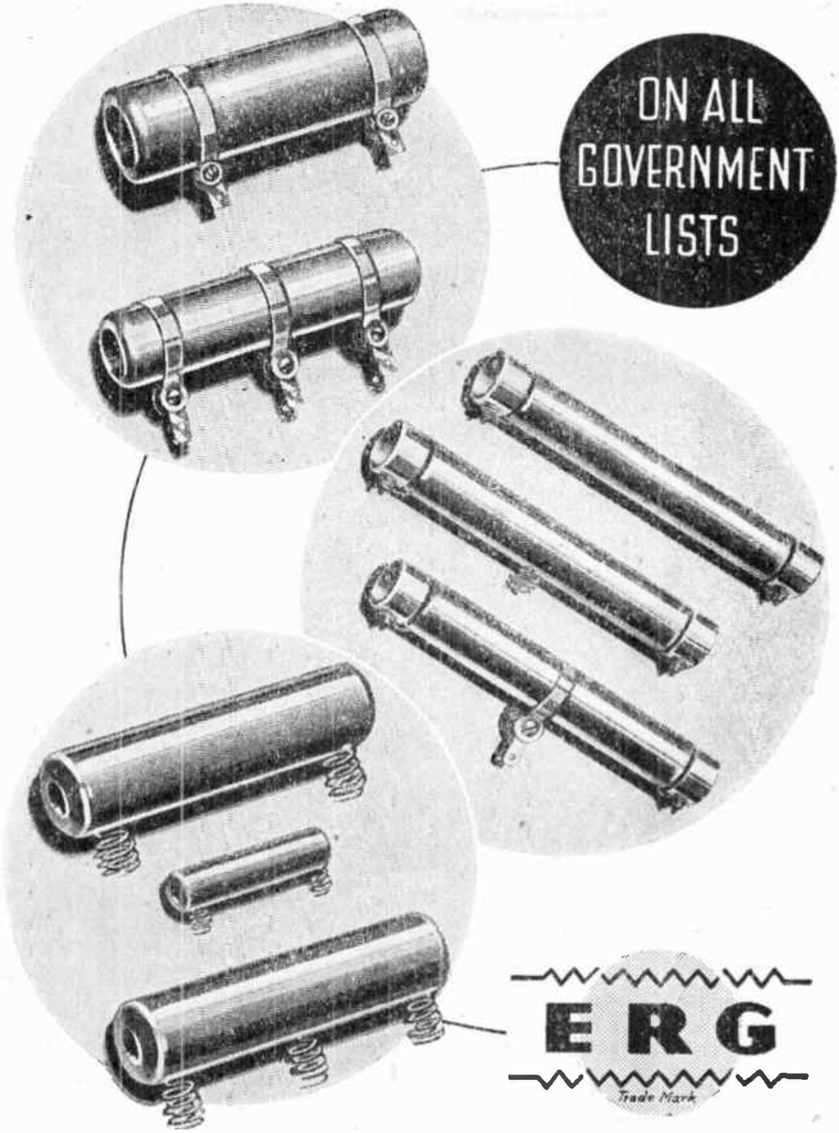
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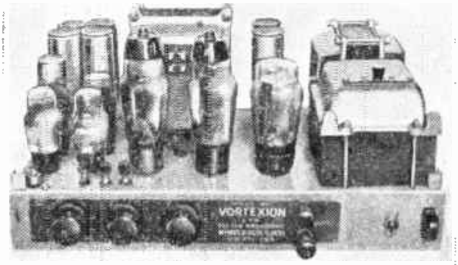
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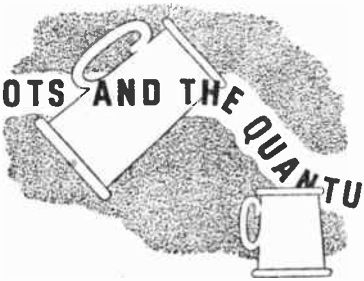

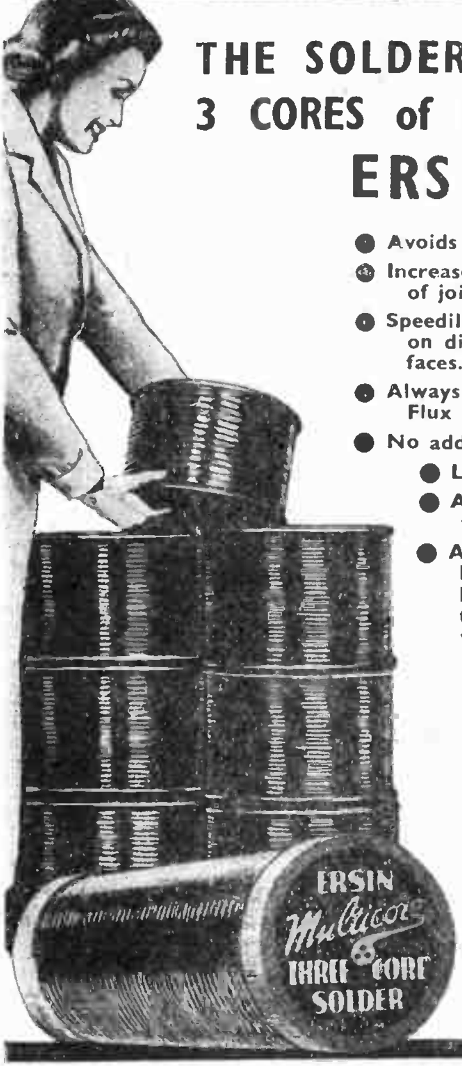
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PRINCIPAL CONTENTS

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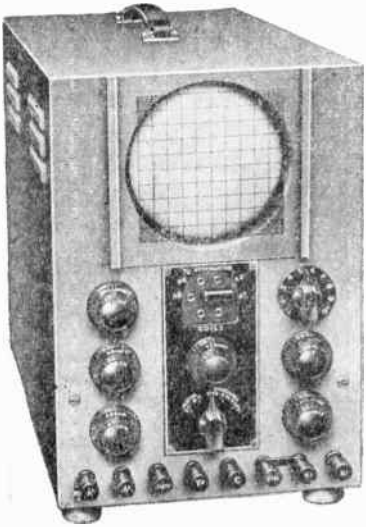
The Council acknowledge with thanks the generous donations of many members to the Institution's Building Fund.

All donations are acknowledged and will be recorded in the Year Book of the Institution.



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British Institution of Radio Engineers

(Founded 1925 Incorporated 1932)

LONDON, ENGLAND

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1942-43

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The

British Institution of Radio Engineers

9 BEDFORD SQUARE,

London, W.C.1

Vol. 3. No. 4. 1942-43 MARCH—MAY, 1943

RECEPTION TO OPEN THE NEW BUILDING

At 9 Bedford Square, W.C.1, March 30th, 1943

A reception held on March 30th marked the opening of the new headquarters of the Institution, which have been necessitated by the continuous growth in membership and the expansion in activities in recent years. The occasion was also noteworthy in that it commemorated the eighteenth year of the Institution's existence.

The Institution was honoured by the presence of many leaders in the fields of industry, research, education and the radio branches of the Services. Each visitor was given a pamphlet, briefly outlining the history and development of the Institution. This showed how a professional body for radio engineers in Great Britain originated with the formation of the British Radio Association in 1922. A link with the formation of that Association was the presence of the Right Honourable Lord Strabolgi at the reception, and the message of goodwill received from His Grace the Duke of Sutherland, P.C., formerly President of the Radio Association.

The pamphlet outlined the Institution's help in the national effort, both prior to and during hostilities, the work of the five main Committees and stressed the importance of a National Certificate in radio engineering. The leaflet continued :—

> " The wide ramifications of radio, now applied to war purposes for offence and defence, but in future to be a means of improving the lot of the citizen in the world at peace, make it essential that the technical status and professional interests of the radio and electronic engineer must be the concern of a body which caters solely for his needs."

The new headquarters of the Institution were formally opened by the Mayor of Holborn and, on behalf of the guests, the Right Honourable Lord Brabazon of Tara, P.C., made a short address emphasising the need for a high standard of qualification for professional radio engineers, and drawing an analogy between the present work of the Institution, representing a modern branch of engineering, and the early days of the Institution of Aeronautical Engineers. His Lordship advocated a high standard of examination, with opportunity for specialisation, as an essential qualification for membership.

The General Secretary, Mr. G. D. Clifford, responding on behalf of the Institution, paid tribute to Lord Brabazon's work for aeronautical engineers. Whilst the original aspect of civil engineering was all embracing and only excluded military engineering, the main applications of science developed so enormously as to necessitate the founding of specialised professional bodies. Radio and electronic engineering was parallel with the main applications of science and not subservient to a main application. Mr. Clifford dealt with the development in strength of the American Institute and the Australian Institution of Radio Engineers and said that the growing membership of the British Institution reflected the increasing importance attached to training properly British radio engineers of the future.

The guests and members, who were received by the President, Sir Louis Sterling, included :—

Air Vice-Marshal R. S. Aitken, D.F.C.
Major T. Aubertin, M.A.
The Mayor of Holborn (Alderman G. J. Bailey, J.P.)
Lord Brabazon of Tara, P.C.
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S. R. Wilkins

A description of the Institution's new headquarters was given in the December-January 1943 Journal. It is hoped that many more members will be able to visit the Institution and take advantage of the library facilities now available.

FORTHCOMING MEETINGS

London : May 26th, 1943.

"Application of Negative Feed-back in Design Principles."

A Paper by S. Hill.

To be held at The Institution of Structural Engineers.

Newcastle-upon-Tyne : June 4th, 1943.

"Microphones and Receivers"

(with special reference to speech communication).

A Paper by L. C. Pocock, M.Sc.

To be held at the Rutherford Technical College,
Bath Lane, Newcastle-upon-Tyne.

London : September 3rd, 1943.

Annual General Meeting and Awards to Examination Prize Winners.

(Sir Stafford Cripps, K.C., M.P., has been invited to address the Institution after the Annual General Meeting.)

London : October 29th, 1943.

"Colour Television."

A Paper by John L. Baird.

London : November 26th, 1943.

"Stabilising Electronic Circuits."

A Paper by M. M. Levy (Associate Member).

London : December 15th, 1943.*

"Selective Methods in Radio Reception."

A Paper by E. L. Gardiner, B.Sc.

London : January 28th, 1943.*

"Ultra Short Waves."

A Paper by J. E. Godeck.

* Provisional dates.

The

British Institution of Radio Engineers

MODERN CONDENSER TECHNIQUE

by

J. H. Cozens, B.Sc., (Hons.), A.M.I.E.E.†

A paper read before the London Section on January 23*rd*, 1943, *and again before the Midland Section in Birmingham, on March* 19*th*, 1943.

INTRODUCTION

This paper deals only with fixed condensers, and these may be considered in four main groups according to the nature of the dielectric, as follows :—

1. Paper Dielectric Condensers.
2. Mica Dielectric Condensers.
3. Ceramic Dielectric Condensers.
4. Electrolytic Condensers.

The first three groups are briefly discussed, their salient features indicated, and one or two points of particular interest referred to in connection with their use. The fourth group, which is perhaps the most interesting from the scientific point of view and appears to be the least well understood, is treated in greater detail. The treatment, even of this group, however, cannot be complete in one short paper, and an attempt is made to emphasise those properties which have received little or no attention in the past, rather than to present a more complete description which would involve a repetition of properties adequately described elsewhere.

2. The Paper Dielectric Condenser

2.1. *General Description.*

Little need be said about the physical form of this type of condenser, which is quite well known. The electrodes consist of metal foils (usually Aluminium but sometimes Tin or Copper) interleaved with paper and rolled into compact form. The paper is specially dried and impregnated in wax or oil. The smaller units are usually housed in tubes of cardboard, bakelised paper or sometimes metal, while the larger units are normally housed in metal boxes.

A good quality paper condenser in a hermetically sealed container will have an insulation resistance of the order of 1,000 to 10,000 megohms for a capacity of 1μF and the power factor will usually be of the order of 0.003. The most frequently met capacities range from 0.001 to 10μF but, of course, capacities up to several hundreds of microfarads are sometimes made for special purposes. Typical uses are for coupling and decoupling in A.F. amplifiers (and sometimes in R.F. circuits) and smoothing of H.T. supplies particularly where heavy ripple currents have to be carried.

---

† Telegraph Condenser Co. Ltd.

2.2. *Non-inductive Condensers.*

A property of paper condensers which appears to cause some confusion from time to time, is the residual inductance, and the term " Non-inductive Condenser " is much misused.

It is easy to understand why the early condensers of this type had a relatively high inductance since the foils form a coil of many turns. The foil material is usually aluminium and contact is made with the foil by inserting lugs of, say, tin or other readily solderable metal. This construction will therefore be referred to as the " lug type."

The first effective method of reducing the inductance was the projection of the foils, one from each end of the roll, so that current could enter and leave along the edge of the coil and thus avoid a circular path. So that the edges may be soldered together, this usually means the use of tin foil which is about 2½ times as heavy as aluminium and has about 4 times the resistivity. This construction, which will be called " extended foil type," is often referred to, both in this country and America, as the " non-inductive type," a distinction which is quite erroneous to-day since by careful design it is now possible to make lug type condensers with inductance no greater than that of the extended foil type.

This point may be illustrated by the following measurements made at a test frequency of 50 mc.

Condenser Type	*Inductance*	*Series Resistance*
Lug type	0.020μH.	0.52 ohm.
Extended Foil type ..	0.014μH.	0.38 ohm.

This test suggests that the lug type has a slightly higher inductance, but the difference is negligible. However, further recent improvements in design have enabled even this difference to be eliminated and some cases have been known of R.F. circuits in which the lug type has given the better performance.

The constructional difference between the lug and extended foil types is indicated in Figs. 1*a* and 1*b*, which show diagrammatically portions of the unrolled condensers.

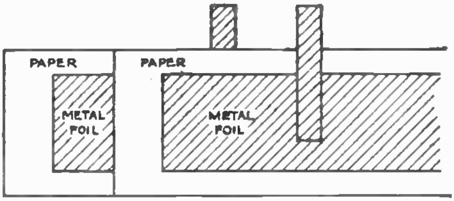

Fig. 1a.—Lug type.

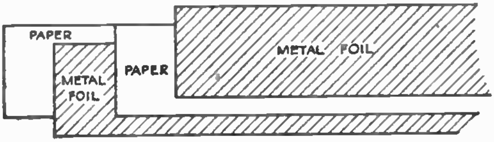

Fig. 1b.—Extended foil type.

The advantage of the extended foil type lies in its lower equivalent series resistance and greater current carrying capacity, but from the foregoing it can be seen that it has no exclusive right to the name " non-inductive." In fact, no condenser can be truly non-inductive, and it would be preferable to use the term " low-inductance condenser," for both the types described above, adding " lug type " or " extended foil type " where necessary, to distinguish between them.

In circuit design, the only paper condensers whose inductance is likely to be of importance, are the tubulars. Fortunately, with these types it is found that the inductance is very nearly independent of capacity and a useful approximation may be obtained by taking the inductance as that of a straight 20 S.W.G. copper wire the length of the condenser (assuming of course that the condenser has been properly designed). This inductance should lie between 0.02 and 0.05μH.

This brings out a very important point and that is the fact that it is useless worrying about the inductance of a condenser if it is connected in circuit with wires several times its own length.

A knowledge of the inductance of a condenser may sometimes be usefully employed by choosing the capacity so that it resonates with its own inductance at some particular frequency and so provides a much enhanced by-pass effect at that frequency. This has actually been done in certain radio interference filters. The reduction of impedance near the resonant frequency is shown compared with the curve for a perfect condenser in Fig. 2.

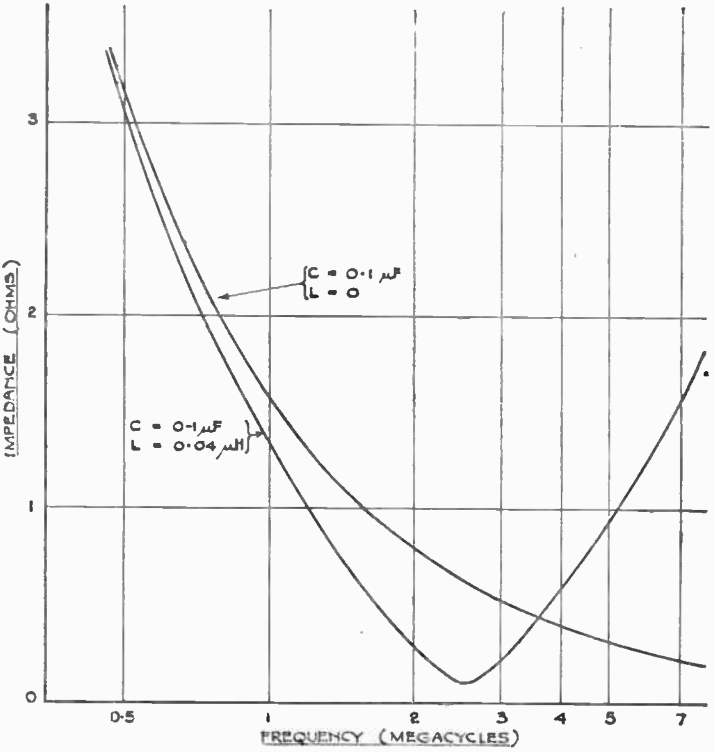

Fig. 2.—Effect of residual inductance on impedance of a 0.1μF condenser.

2.3. *Sealing of Tubular Condensers.*

The greatest enemy of the paper condenser is moisture, and not only must this be removed as thoroughly as possible during manufacture but the finished product must be protected against the ingress of moisture during service or storage.

The hermetic sealing of the larger condensers housed in metal boxes does not present a great deal of difficulty, but the smallness of the tubular condenser complicates the problem somewhat.

The majority of the tubular condensers are contained in impregnated paper tubes and the commonest method of protecting them against moisture is to give them a good coating of a suitable wax. Condensers thus treated can give very good performance under conditions of high humidity. Recently, however, there has arisen a demand for tubular condensers to withstand extremely severe tropical conditions, and new methods of sealing have consequently been developed.

One such method involves the use of a bakelite moulded tube having a moulded-in terminal at each end. The tube is made in two halves which are cemented and clamped together after insertion of the condenser unit, and connecting wires are brought out through the hollow terminal stems which are subsequently sealed by soldering.

A modification of this form employs a tube moulded in one piece with a cylindrical metal insert at each end, the insert being spun over on to a metal disc with a suitable gasket between to provide the seal.

A third method retains the paper tube but treats this with a special material which renders the tube moisture proof to a greater degree than the simple wax coating.

The fourth method is to use a ceramic tube as a container, to metallise the ends of the tube and solder caps on the ends to give complete sealing. A variation of this method is to use a metal tube and close the ends by soldering on a ceramic disc which has been metallised round the edge, the wire being brought out through a small hole in the disc and sealed in by soldering.

The fifth method, which is perhaps the most recent, makes use of a glass tube which is sealed, either in a similar manner to the ceramic tube or by means of end caps similar to bottle closures of the screw on or press-on variety.

The thoroughness of the sealing of all these types results in condensers of extremely high resistance to severe tropical conditions.

2.4. *Harmonic Analysis.*

A very simple application of the paper condenser which the author has found useful is in the analysis of low frequency voltage wave-forms.

A wave which has only a small harmonic content is often difficult to analyse, particularly if its deviation from true sine wave-form is only of the same order of magnitude as the thickness of the oscillograph trace.

The method is to connect a condenser across the supply to be examined and record the wave-form of the current through the condenser. The current through the condenser is proportional to frequency so that the harmonics will be amplified according to their order. This is useful since it usually happens that the higher the harmonic the smaller its magnitude in the original wave-form.

The analysis is therefore carried out on the current wave-form, where the harmonics are amplified, and then the second harmonic is divided by 2, the third by 3, the fourth by 4 and so on to obtain the analysis of the original voltage wave. Fig. 3a shows the apparent absence of harmonics in a particular voltage wave, while the corresponding condenser current wave (Fig. 3b) shows the harmonics clearly.

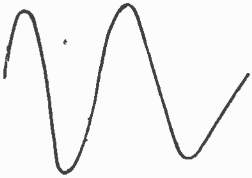

Fig 3a.

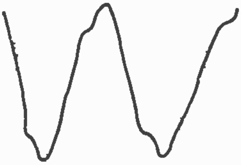

Fig. 3b.

2.5. *Spark Suppression.*

A use which has grown up very rapidly of late is the suppression of sparking at the contacts of D.C. switches, usually thermostatically operated. As an example of what can be done in this direction, a certain thermostat whose contacts were rated for 15 A. A.C. but only 0·1 A. D.C. could, after the fitting of a suitable condenser, be rated for 15 A. on either A.C. or D.C.

Many people appear to have the impression that a resistance should be used in series with the condenser for spark suppression, but this is seldom advisable and, frequently, even a small resistance will ruin the effect of the condenser when currents of 1 A. or more are being handled.

It is not usually possible to calculate the optimum capacity for a given circuit, and the capacity is best found by trial and error. Generally speaking, the larger the capacity, the smaller the spark as the contacts break, but the greater the spark due to condenser discharge when the contacts close. Provided that the switch is well designed and has contacts of adequate area, a capacity can usually be found which will give negligible sparking both at make and break.

When the load is resistive the condenser should be connected directly across the contacts and need be rated at no greater voltage than that of the supply. If the load is inductive, it may be found better to connect the condenser permanently in parallel with the load, and in some cases one in each position may be the best arrangement. This point should be decided by trial.

With an inductive load, voltage peaks much higher than the supply voltage may occur, and the condenser must be rated accordingly. It is possible to reduce the inductive surge by means of the condenser, but more will be said about that in the section on electrolytics.

2.6. *Paper Condensers used on A.C.*

In general, paper condensers rated up to 450 V. D.C. may be used on A.C. provided that the peak voltage does not exceed the D.C. voltage rating of the condenser. It does not follow, however, that a condenser of higher D.C. voltage rating is suitable for A.C. operation at equivalent peak voltage. It is a good general rule not to apply more than 300 V. R.M.S. to any D.C. condenser, whatever its voltage rating, without first consulting the makers, since A.C. rating in excess of 300 V. R.M.S. usually calls for special design.

It might appear, at first sight, unnecessary to emphasise this point, but the Author has known many instances where its incomplete understanding has led to trouble. For example, if a condenser is charged and discharged rapidly, as may occur in a time base circuit, it is often forgotten that this is equivalent to applying a steady D.C. potential with a superposed alternating potential, and if the charging voltage is high enough, the A.C. component may have a harmful effect on the condenser, even though the latter has a D.C. rating in excess of the charging voltage.

3. Mica Condensers

Little need be said about this type, since it has undergone only slight changes in recent years except for the development of the silvered mica types.

The general form of mica condenser is quite well known and consists of alternate layers of mica and metallic foil electrodes held together by some form of clamp.

The chief characteristic of this type of condenser is its low power factor, usually of the order of 0.0003 to 0.0005, which remains sensibly constant with varying frequency and renders the condenser particularly suitable for use in R.F. circuits where low loss is required.

In the silvered mica condenser the electrode takes the form of a silver film deposited by a special technique on the mica. Since this film adheres closely to the mica and excludes any possibility of air pockets or relative motion of electrode and dielectric, a high degree of stability is attained.

4. Ceramic Condensers

4.1. *General.*

In this type of condenser a ceramic body, having in the simplest case the form of a disc, is given a metallic coating (usually silver) on the opposite parallel faces to provide the electrodes, the ceramic material forming the dielectric.

A discussion of this class of condenser becomes largely a discussion on the electrical properties of the various ceramic materials and might well form the subject of a separate paper. In this instance only the outstanding general properties which typify this class will be mentioned.

4.2. *Properties and Types of Materials.*

Perhaps the most interesting property of these ceramic bodies is their low power factor at radio frequencies and the fact that the power factor improves with increasing frequency, making them especially suitable for short wave working.

The ceramic materials fall into two main classes. The first class have a base of soapstone, are white in appearance, have permittivity of the order of 6 and give condensers with a positive temperature coefficient of capacity of the order of 10^{-4} per degree C. Frequentite, Frequelex and Calit are examples of this class. The second class have a base of Titanium Dioxide (Rutile) and are light brown or buff in colour. They have a phenomenal permittivity of the order of 80 and produce condensers with a negative capacity temperature coefficient of 6 to 8×10^{-4} per degree C. Examples of this class of material are Faradex, Permalex and Condensa. Condensers made with the Rutile type of body usually have a high power factor at audio frequencies, but the improvement wtth increase of frequency is sufficient to make the power factor satisfactory at radio frequencies.

However, recent research has shown that it is possible to make a ceramic body of high permittivity and negative capacity temperature coefficient which has a good power factor throughout the frequency range from very low audio frequencies upwards.

4.3. *Compensated Temperature Coefficient.*

An interesting application is the use of the negative temperature coefficient material to balance out the positive temperature coefficient of the coil in a tuned circuit. By using two condensers in parallel, one having a positive and one a negative temperature coefficient, any temperature coefficient can be obtained between the two extremes by choosing the appropriate ratio for the two capacities.

5. Electrolytic Condensers

5.1. *General.*

The outstanding feature of this type of condenser is the large capacity which can be obtained in a given volume, particularly when the applied voltage is low.

With a paper dielectric condenser the size for a given capacity depends upon the voltage rating, but the 200 V. condenser is usually the smallest obtainable since the dielectric of the 200 V. condenser is the thinnest paper normally available. No further reduction in size is possible therefore, even though the working voltage may be much below 200.

In the case of the electrolytic condenser the reduction in size with decreasing voltage rating can be carried right down to about 3 volts, so that for very low working voltages enormous capacities can be obtained in a small space. As an example, a condenser of capacity of 20,000μF for 3 volt working can be made in a box 3 in. × 4 in. × 2½ in., and the construction of a condenser of capacity 1 Farad, once thought quite fantastic, now becomes quite a simple matter. It is interesting to reflect that if we consider the sun as a spherical conductor, its radius being 432,000 miles, it will have a capacity of only 0.08 Farad, and an electrolytic condenser of this capacity could be contained in a box measuring 5 in. cube.

5.2. *Nature of the Dielectric.*

The nature of the dieletric merits some discussion since, although it has been well treated in various publications, an appreciation of certain points is essential to a useful understanding of some of the properties of these condensers.

About the middle of the nineteenth century it was discovered that an electrolytic cell could behave as a condenser, and eventually it was observed that with certain electrode materials the capacity varied greatly with the applied voltage, while with other materials, notably aluminium, the variation of capacity with voltage was quite small. Accordingly two classes of electrolytic condenser are recognised, (*a*) the polarisation type, using, for example, platinum electrodes, and (*b*) the oxide film type with electrodes of, say, aluminium.

The differences between these two types will be referred to later. It is the oxide film type which has undergone such rapid development during the past 15 years.

If a piece of aluminium is made the anode of an electrolytic cell containing a solution of ammonium borate and the cell is connected, in series with a resistance, to a D.C. supply, a current will flow, limited initially only by the resistance. This current will gradually diminish and at the same time the voltage across the cell will rise, the rate of change of current and voltage decreasing with time so that each will gradually settle down to a steady value.

On removing the aluminium from the cell it will now be found to have a coating of aluminium oxide produced by the oxygen liberated by electrolysis, and it is this oxide which forms the dielectric of the electrolytic condenser. The oxide film is transparent, but it can usually be detected by visual inspection owing to the interference colours which it produces. Sometimes the thicker films appear to have a greyish tint. This process, which produces the oxide film on the aluminium, is known as " forming " or " anodising."

The interference colours are an indication of the extreme thinness of the film and it is interesting to attempt to estimate the film thickness by observation of these colours.

For a given anode surface area the capacity obtained is found by experiment to be inversely proportional to the voltage used in the formation process, from which it follows that the thickness of the film is proportional to the forming voltage. Now from the theory of physical optics it may be deduced that a film of transparent material will appear coloured if the thickness of the film is given by the relation

$$t = \frac{n\lambda}{2\sqrt{\mu^2 - \sin^2\theta}} \quad \text{or} \quad t = \frac{(2n+1)\lambda}{4\sqrt{\mu^2 - \sin^2\theta}}$$

according as the light does or does not suffer a reversal of phase on reflection at the inner surface, where

t=thickness of film
μ=refractive index of film
θ=the angle of incidence
λ=the wavelength of the light removed by interference
n=a small integer.

Thus, taking the shortest wavelength of visible light to be 4,000 Å, $\mu=1.5$, which seems to be a reasonable approximation, and $\theta=o$ i.e. normal incidence, the thinnest film which should show colours would have a thickness of 1,333 Å or 666 Å.

The thickness of the film for a given formation voltage varies somewhat with the electrolyte used and the details of the process, but for one particular process the 100 volt foil is the lowest voltage foil which shows any colours except for very large angles of incidence. With this foil formed at 100 volts, a surface area of 17·6 cm². is required to give a capacity of 1 μF whence the permittivity k of the film may be calculated from the formula $k=\frac{4\pi tC.}{A}$ If the thickness is 1,333Å, this gives k=8·6 while t=666Å gives k=4·3. The observed value of k for pure dry aluminium oxide is about 7·8 which suggests that the first formula mentioned above for thickness is the correct one to use and the thickness of film on the 100 volt foil is approximately 1,300Å thick. Even the thickest film therefore, formed at about 600 volts will have a thickness only of the order of the wavelength of red light.

Bearing in mind the fact that the capacity of a parallel plate condenser is inversely proportional to the thickness of the dielectric between the plates, it will now be readily understood how the electrolytic condenser can have such a large capacity.

It is interesting to note that aluminium has a very great chemical affinity for oxygen and that on exposure to air, the metal rapidly grows a very thin transparent film of oxide so that it is practically impossible to obtain aluminium without at least a thin film on its surface, a fact which has sometimes been the cause of high resistance contact on an aluminium chassis. This film is generally found to have a thickness of the order of 50Å. and Professor Mott has shown by the use of quantum mechanics that this is the maximum thickness which could develop at normal temperatures without the addition of energy to the electrons of the metal. Thus it is possible to use aluminium in its normal state to form a condenser which will operate at very small potentials but of course the oxide is not in its best form and the practice is not recommended.

A further interesting point about Professor Mott's work is that he has reached the conclusion that the film builds up, not by oxygen penetrating the oxide layer and combining with aluminium at the bottom of the layer, but by the movement of metallic ions through the oxide layer to combine with oxygen at the surface.

5.3. *Etched Anodes.*

An important development which resulted in an even greater capacity per unit volume of condenser was the roughening of the anode to increase its surface area. If the electrodes of a paper dielectric condenser were roughened, no advantage would be gained since the thickness of the dielectric would be large compared with the undulations on the electrode surface, and further, the contour of the second electrode could not be made to follow that of the first so that, if anything, a loss of capacity would result because the mean distance between the electrodes would be increased. This is illustrated in Fig. 4 (*a*) in which the thickness of foil and paper is exaggerated for the sake of clarity.

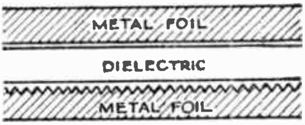

Fig. 4a.—Section of paper dielectric condenser with one electrode etched.

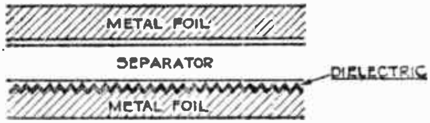

Fig. 4b.—Section of electrolytic condenser with one electrode etched.

In the case of the electrolytic condenser the dielectric is so thin that it readily follows the contour of the anode and since the true cathode is the electrolyte this also is able to conform to the irregularities of the anode surface as shown diagramatically in Fig. 4 (*b*). In this way the capacity may be increased by as much as 10 times, though in practice the gain is usually adjusted to between 2 and 5 times.

The roughening may be performed by mechanical means, which can seldom be made to give an increase of more than 2 : 1, or by etching which can be made to give much larger increases. Generally speaking, the higher the voltage to which a foil is formed the more difficult it is to get a high gain because the thicker oxide film tends to level out the surface of the anode.

5.4. *Practical Forms.*

The electrolytic condenser may be classified into " wet " or " aqueous " types and " dry " types. A third class, the " semi-dry " type is sometimes referred to but this is so similar in construction to the dry type that no separate discussion is needed here.

The wet type consists generally of a rigid aluminium anode, upon which an oxide layer has been formed, rigidly mounted in a cylindrical metal container (usually aluminium) filled with electrolyte. This type is obsolescent but is briefly described here as a step in the understanding of the electrolytic condenser.

It is important to realise that the central aluminium electrode is the anode of the condenser, the oxide film is the dielectric and the solution is the cathode, the very small spacing between the anode and cathode being responsible for the large capacity obtained. The metallic container is frequently referred to as the cathode and this is convenient but not strictly correct since it is really only a means of making contact with the true cathode i.e. the solution.

A few years ago, before the dry type reached its present stage of development, the wet type was the more reliable and was recommended in preference to the dry, but now that the dry type can be made as reliable as the wet the latter is falling into disuse. This is not surprising since, while the wet type must be mounted upright in operation, the dry type can be mounted in any position and further has better electrical characteristics.

The general form of the dry electrolytic unit is very similar to that of a paper dielectric condenser. Two aluminium foils, one with an oxide film and one without, are interleaved with paper or other suitable material and rolled up into a compact cylindrical form. The paper or other separator is saturated with electrolyte the consistency of which may be anything from that of a viscous liquid to a hard fudge-like cream, depending on the technique of the manufacturer: This electrolyte usually contains ammonia in combination with boric acid and some form of polyhydric alcohol such as glycerol or ethlene glycol.

The oxide film is put on to the positive foil by passing it continuously through an electrolytic bath of which it forms the positive pole. The bath itself usually forms the negative pole and the applied voltage is rather more (say 20%) than the voltage at which the condenser will be rated. The other foil, usually called the negative foil, is untreated and serves to make intimate contact with the electrolyte and so minimise the effective series resistance of the condenser.

One end of each foil is folded back to form a lug projecting at right angles to the length of the foil and these lugs provide means of making connection from the condenser unit to the terminals.

The finished unit must be assembled in a container and hermetically sealed because the electrolyte is usually hygroscopic and increase of moisture content would be detrimental. The container is preferably of aluminium but may be of inert non-metallic material such as bakelite. Sometimes tin plate is used for the container but then the unit is usually wrapped in some way to prevent the electrolyte making contact with the case.

5.5. *Properties.*

The principal properties of the electrolytic condenser are as follows.

(*a*) *Capacity.* This is very large for a given bulk and does not vary greatly with applied voltage.

In the polarisation type of cell consisting, say, of a pair of platinum plates in dilute sulphuric acid, the dielectric appears to be a layer of gas on the electrode surface and the capacity obtained depends on the applied voltage and increases very rapidly with increasing voltage.

With the oxide film type however, this effect does not occur, the charge of capacity with applied voltage being small, and usually there is a slight decrease in capacity with increasing voltage.

(*b*) *Power Factor.* Compared with other classes of condenser, the power factor of electrolytics is high. It may be anything from 2% to 30% at 50 c.p.s. depending on the type.

As a useful rough approximation, the electrolytic condenser may be considered to consist of a perfect capacity in series with a fixed resistance. Thus the power factor will be roughly proportional to frequency for low audio frequencies and will tend to unity at high frequencies. This does not necessarily mean that the condenser is useless at high frequencies, since it will still discriminate between A.C. and D.C.

(*c*) *Insulation Resistance.* This is low compared with other types and is usually between 5 and 50 megohm-microfarads. For this reason leakage current is usually specified rather than resistance. Leakage increases with, and at a slightly greater rate than, applied voltage, until the rated voltage is exceeded, after which the leakage current increases very rapidly.

(*d*) *Temperature Coefficient.* Increase of temperature brings about an increase of capacity and leakage current and a decrease in power factor. The latter property is useful in helping to prevent excessive temperature rise due to ripple currents.

The temperature coefficients of capacity and power factor are not unduly great at normal room temperatures but begin to increase rather rapidly when the temperature drops below about −20° C. However, new types are in the course of development which will operate satisfactorily at very much lower temperatures.

5.6. *Applications.*

Some of the applications of electrolytic condensers will now be discussed.

5.6.1. *Reservoir Condensers.*

Probably a greater number of electrolytic condensers have been used for smoothing the H.T. supply to radio receiver circuits than for any other purpose. The condensers used in the H.T. supply circuits are usually 4, 8, 16 or 32μF. and may be considered under two headings, viz. Reservoirs and Smoothers.

The reservoir condenser performs two functions. One is to increase the mean voltage output of the rectifier and the other is to confer some measure of smoothing on the output. The voltage across the reservoir condenser is a fluctuating one and may be considered as a steady D.C. component, plus an A.C. component usually known as the ripple voltage. The fundamental frequency of this ripple voltage is equal to that of the supply for half-wave rectifiers and voltage summation circuits and twice that of the supply for current summation and bridge circuits.

Now when an alternating potential E exists across a condenser of capacity C farads, a current flows through the condenser of magnitude $E\omega C$ where ω is 2π times the frequency, and thus an appreciable alternating current flows through the reservoir condenser. In normal commercial radio circuits, this ripple current may be anything from 50 to 150 mA R.M.S., and its value should be carefully considered when choosing the reservoir condenser to ensure that it does not exceed the maker's rating.

The power factor of the condenser may be taken as that fraction of the total alternating current through the condenser which is in phase with the applied voltage and so causes the generation of heat in the condenser. For a reservoir condenser, therefore, it is desirable that the power factor should be as small as possible since in most cases the generation of heat is the factor which limits the amount of ripple which the condenser can safely carry.

The ripple current through the reservoir is approximately proportional to the D.C. output current, so that for small current outputs it may be neglected. The best procedure is of course to measure the ripple current to ensure that the rating is not exceeded, but, as a guide to a preliminary choice, the condenser will most probably be safe from the ripple aspect if the following conditions are not exceeded.

Capacity μF.	D.C. Output.			
	Plain Anode		Etched Anode	
	Half-wave	Full-wave	Half-wave	Full-wave
4	30 mA.	60 mA.	20 mA.	40 mA.
8	45 mA.	85 mA.	30 mA.	60 mA.
16	60 mA.	120 mA.	40 mA.	80 mA.
32	90 mA.	170 mA.	60 mA.	120 mA.

The column headed " Half-wave " includes the voltage doubler, which is essentially two half-wave rectifiers in series, and the " Full-wave " column refers to the usual current summation circuit and to bridge rectifiers.

It is emphasised that the above figures are not meant as hard and fast ratings, since these will naturally vary from one type to another, but are intended as a guide where ripple currents cannot readily be measured or the ripple rating of the condenser is unknown.

As a further guide, if the circuit is run for half an hour or so delivering full load and no appreciable temperature rise in the reservoir condenser can be observed, then the ripple current is not likely to be excessive.

One other point has to be observed in choosing the reservoir condenser and that is that it must be rated to withstand the maximum peak voltage which will be applied to it, and this will often be considerably more than the D.C. output. In actual fact it will be the output voltage plus the voltage drop in the smoothing choke plus the peak of the ripple voltage. The condenser may thus easily have to withstand 50 or 100 volts in excess of the output voltage.

5.6.2. *Smoothing Condensers.*

It has been stated above, that for the reservoir condenser a low power factor is required, and it is often suggested that low power factor is the chief criterion of a good condenser. This, however, is not true since low power factor may be obtained in manufacture at the expense of breakdown voltage, leakage current and condenser life. It does not follow, therefore, that of two condensers, the one with the lower power factor is the better condenser. In fact, the higher power factor condenser may be the better of the two in all respects, including smoothing efficiency as will be shown later.

In a smoothing condenser, power factor is of little importance provided that it does not exceed 30%, and even values higher than this may sometimes be used without loss of smoothing efficiency.

It is commonly assumed that in a filter circuit such as Fig. 5, the output ripple voltage is proportional to the condenser impedance. This is not strictly true, but let it be taken as true for the moment. Then the curve of Fig. 6 showing variation of impedance with power factor for a condenser of fixed capacity, will show that power factors up to 30% may be neglected and further indicates that a power factor of even 50% means an increase of only 15½% in the impedance and hence an increase of only 1·25 dB. in hum level.

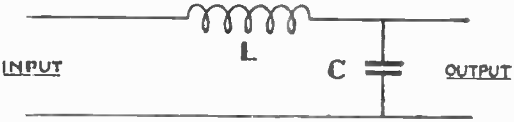

Fig. 5.—Simple smoothing circuit.

Now consider two condensers, A and B, and suppose A has capacity 8·0μF and power factor 2%, while B has capacity 8·1μF and power factor 15%. A would probably be the most popular choice for a smoothing circuit, but, in actual fact, its impedance is equal to that of B, and furthermore, as will be shown later, B will provide even better smoothing than A. Also it is possible that A would have a higher leakage and a shorter life than B. It must be remembered, too, that the manufacturer's capacity tolerance is never less than 10% (it is usually $-10\%+50\%$) and this would swamp any variation in impedance due to power factor.

It thus appears that, provided a designer has the slightest margin in hand on his smoothing capacity, he need not worry unduly about the power factor of the condenser, and it might even be suggested that he should specify a minimum value for power factor because, for maximum smoothing efficiency, there is an optimum value of condenser power factor which is not zero as is popularly supposed.

It is instructive to consider in greater detail the effect of power factor on smoothing, and the simple smoothing filter having a series choke and shunt condenser as shown in Fig. 5 is taken as a basis for this investigation.

To simplify the calculation it will be assumed that the load impedance is large compared with that of the condenser and does not appreciably affect the impedance measured between the condenser terminals.

The symbols used are as follows :—

X_C = Condenser reactance $\quad$ X_L = Choke reactance

Z = Condenser impedance $\quad$ Z_L = Choke impedance

ϕ = Condenser phase angle $\quad$ θ = Choke phase angle

R_C = Effective series resistance of condenser $\quad$ R_L = Effective series resistance of choke

Z = Impedance of choke and condenser in series

S = Smoothing ratio = ratio of input ripple voltage to output ripple voltage.

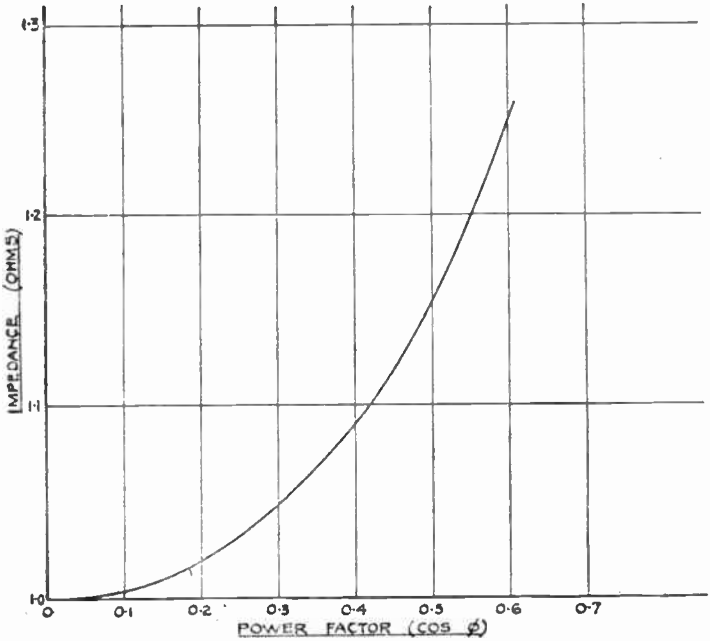

Fig. 6.—Relation between impedance and power factor for condenser of unit reactance.

From the vector diagram Fig. 7 :

$$Z_C^2 = Z^2 + Z_L^2 - 2\,Z_C\,Z_L \cos\left[\,\pi - (\theta + \phi)\right] \;\dots\dots\; (1)$$

Whence
$$\left(\frac{Z}{Z_C}\right)^2 = 1 + \left(\frac{Z_L}{Z_C}\right)^2 + 2\left(\frac{Z_L}{Z_C}\right)\cos(\theta + \phi) \;\dots\dots\dots\; (2)$$

Now suppose that the condenser has constant impedance but its power factor may vary. Then $\left(\frac{Z_L}{Z_C}\right)$ will be a constant, say k, and the smoothing ratio S which is equal to $\frac{Z}{Z_C}$ will be given by the relation

$$S^2 = 1 + k^2 + 2k\cos(\theta+\phi)$$

which means that S will increase continuously as $(\theta+\phi)$ decreases, reaching a maximum value when $\phi=0$ since θ is fixed and ϕ cannot be negative.

Hence of two condensers of equal impedance that with the higher power factor will give the higher smoothing ratio.

Now consider the effect of varying the power factor of a condenser of fixed capacity. In this case X_C is constant while Z_C and ϕ are varied.

From the vector diagram, $Z_C = \dfrac{X_C}{\sin\phi}$ and substituting this value in the R.H.S. of equation (2) gives

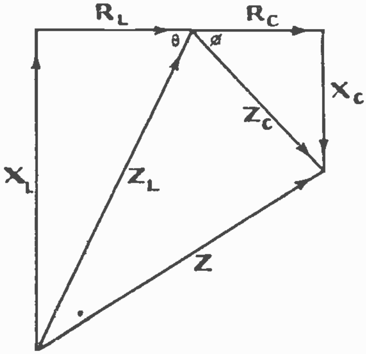

Fig. 7.—Vector diagram for circuit of Fig. 5.

$$\left(\frac{Z}{Z_C}\right)^2 = 1 + \left(\frac{Z_L}{X_C}\right)^2 \sin^2\phi + 2\left(\frac{Z_L}{X_C}\right) \sin\phi \cos\,(\theta+\phi)$$

$$\text{i.e. } S^2 = 1 + A^2 \sin^2\phi + 2A \sin\phi \cos(\theta+\phi) \quad \ldots\ldots\ldots(3)$$

$$\text{Where } A = \frac{Z_L}{X_C} \text{ which is a constant.}$$

To find the condition that S may be a maximum, differentiate equation (3) thus : —

$$\begin{aligned}\frac{d\,(S^2)}{d\phi} &= 2A^2 \sin\phi \cos\phi + 2A[\cos\phi \cos\,(\theta+\phi) - \sin\phi \sin\,(\theta+\phi)] \\ &= A^2 \sin 2\phi + 2A \cos\,(\theta+2\phi) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4) \\ &= A^2 \sin 2\phi + 2A\,(\cos\theta \cos 2\phi - \sin\theta \sin 2\phi) \\ &= A\,(A - 2\sin\theta) \sin 2\phi + 2A \cos\theta \cos 2\phi \quad \ldots\ldots\ldots\ldots (5)\end{aligned}$$

When S is a maximum S^2 is also a maximum and $\dfrac{d\,(S^2)}{d\,\phi} = 0$.

i.e. $(2\sin\theta - A) \sin 2\phi = 2\cos\theta \cos 2\phi$

$$\tan 2\phi = \frac{2\cos\theta}{2\sin\theta - A} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

To proceed further it is necessary to assign values to A and θ and in order to work an example A will be made 10 and $\theta = 60°$.

$$\text{Then}\quad \tan 2\phi = \frac{2\cos 60°}{2\sin 60° - 10} = -\,0.1209$$

$$\text{and } \phi = -\,3°\,27' \text{ or } 86°\,33'$$

The negative angle is obviously inadmissible and the positive angle will give either a maximum or a minimum value for S. To test this, differentiate equation (4) giving

$$\begin{aligned}\frac{d^2\,(S^2)}{d\,\phi^2} &= 2A^2 \cos 2\phi - 4A \sin\,(\theta+2\phi) \\ &= 2A\,[A \cos 2\phi - 2\sin\,(\theta + 2\phi)] \quad \ldots\ldots\ldots\ldots\ldots\ldots (7)\end{aligned}$$

Substituting $\phi = 86°\,33'$ gives

$$\begin{aligned}\frac{d^2\,(S^2)}{d\phi^2} &= 20\,[10 \cos 173°\,6' - 2 \sin 233°\,6'] \\ &= -\,166{\cdot}58\end{aligned}$$

and hence $\phi = 86^\circ\ 33'$ gives a maximum value for S, which means that the condenser will be most efficient in the smoothing circuit if its power factor ($\cos\theta$) is 0·06 or 6% and to reduce the power factor below this figure would increase the output ripple voltage.

From the formulæ developed above it becomes clear that the optimum condenser power factor is never zero except in the impossible case when the choke power factor is zero.

That the optimum power factor for a smoothing condenser is not zero may be confirmed experimentally by the simple circuit of Fig. 8, where C_2 is a condenser of negligible power factor and R is a variable resistance inserted in series with C_2 to give the effect of increasing its power factor. The output ripple voltage is measured on the A.C. voltmeter V which contains a small condenser to isolate it from D.C. If R, initially zero, is gradually increased, the output ripple voltage measured by V will be found to decrease gradually until a certain value of R is reached, after which further increase of R will produce an increase in the reading on V. The optimum value of R found in this way is usually rather higher than that indicated by the theory outlined above and further investigations on this point are being carried out.

It is interesting to note that if the series choke of the filter circuit be replaced by a pure resistance, as it might be for a high impedance load circuit, a similar set of conditions will be found to obtain, the appropriate formulæ being derived by putting $\theta = 0$ in equations (1) to (6).

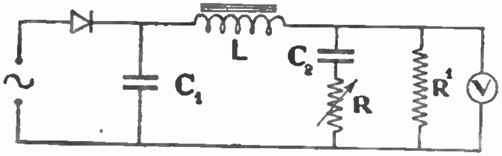

Fig. 8.—Circuit for demonstration of optimum power factor for smoothing condenser.

5.6.3. *Surge Absorbing Condensers.*

The electrolytic condenser can be very usefully employed for preventing dangerous voltage rise occurring when a highly inductive circuit carrying a direct current is broken.

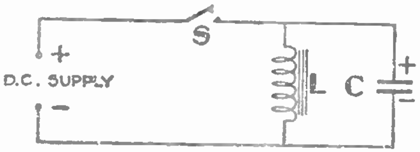

Fig. 9.—Electrolytic condenser used to absorb inductive surge.

The condenser is connected as shown in Fig. 9 and acts more as an asymmetric conductor than a condenser although the capacity does help. While a steady current flows through L, the current through C is very small but when the switch S is opened and the main current interrupted, the induced e.m.f. in L is in such a direction that a current flows through the condenser in its reverse (i.e. low resistance) direction and the energy stored in L is dissipated.

In an actual case the following measurements were made on an electromagnet energised from a 300V. D.C. supply, the peak voltage across L being measured at the instant S was opened.

Type of Condenser	Capacity (μF)	Peak Voltage
Paper	1	2,550
Paper	2	2,000
Paper	4	1,700
Paper	10	1,100
Electrolytic (reversible)	8	500
Electrolytic (polarised)..	8	150

5.6.4. *Welding Condensers.*

An interesting application of electrolytic condensers is in spot welding. For this type of work a condenser of many thousands of microfarads is charged and then discharged through the primary of a specially designed welding transformer.

This method of spot welding has two great advantages over other methods. Firstly, it enables the energy used in each weld, and hence the quality of the weld, to be controlled with great accuracy and secondly, it almost completely eliminates the fluctuations of mains voltage which result from the very heavy transient currents taken by the standard type of spot welder.

The latter advantage results from the fact that the condenser welder draws its energy relatively slowly from the mains as the condenser charges up, the stored energy in the condenser being released in a relatively short time to make the welds, whereas the standard type of welder takes its short bursts of energy straight from the mains as required, resulting in the well known voltage fluctuations.

5.7. *Testing.*

In view of the uses to which electrolytic condensers are put, the relatively large changes which occur with change of temperature and the wide manufacturing tolerances, it is but very rarely that accurate measurements of the characteristics of these condensers are required. In fact, very precise determinations are generally confined to the manufacturers' laboratories and for this reason the few hints on testing which follow are intended, not for the condenser specialist but for the general worker who may want to make rough measurements without purchasing special apparatus.

5.7.1. *Measurement of Capacity.*

The simplest method of measuring capacity is by a measurement of impedance. The condenser is connected in series with an ammeter or milliameter, according to its suspected capacity, and a small alternating voltage applied as shown in Fig. 10. The current which flows through the condenser is given by $I = E\omega C$ whence $C = \frac{I}{\omega E}$ farads. The filament winding of a mains transformer is a useful voltage source and its nominal voltage may be used for calculation purposes but it is better to connect a high impedance voltmeter across the condenser to measure the true voltage. An

Avometer may well be used for this purpose and some models have a scale already calibrated in microfarads.

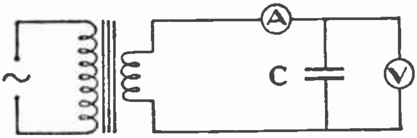

Fig. 10.—*Capacity measurement by impedance method.*

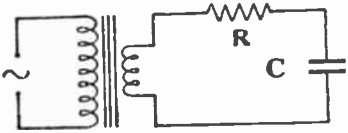

Fig. 11.—*Capacity measurement by comparison of P.D. across C and R.*

A variation of this method is to use a series resistance of known value as shown in Fig. 11 and to measure the voltages E_R and E_C across resistance and condenser respectively. Capacity is then given by $C = \frac{E_R}{\omega R E_C}$ farads.

Perhaps the best modification, if many tests are contemplated, is to use the circuit of Fig. 10 and calibrate the ammeter by means of condensers of known capacity. Some resistance in series with the meter is desirable to prevent the latter being damaged by short-circuits.

No account of power factor is taken in the above methods and this is seen to be justified for rough measurements by the discussion in 5.6.2 above.

It will be noted that no provision is made for a polarisation voltage and, despite the oft repeated advice to the contrary, no polarisation is necessary. The accuracy does not warrant it, and the condenser will certainly not be harmed by application of a small alternating voltage for the short period required to make a test.

In many instances a capacity bridge will be available, and this, too, may be used without the simultaneous application of a polarisation voltage.

With either of the above methods it is good practice to apply to the condenser a D.C. polarising voltage equal to, or a little less than, the rated voltage, just prior to the capacity test, but this is a much simpler procedure than applying the D.C. and A.C. together. The period between the removal of the condenser from the D.C. circuit and the capacity test should not be more than about 5 minutes.

5.7.2. *Measurement of Power Factor.*

A bridge method is desirable for the measurement of the power factor of an electrolytic condenser and a very satisfactory circuit is the series resistance modification of the De Sauty Bridge (see " Alternating Current Bridge Methods," B. Hague, Pitman).

Since the power factor to be measured is high, a good quality paper condenser can be used as a standard.

The test frequency should be 50 c.p.s. and the filament winding on a mains transformer is a convenient source. As in the case of the measurement of capacity, it is not necessary to apply a polarising voltage during the actual measurement, but it is desirable to do so for a few minutes immediately before making the measurement.

5.7.3. *Measurement of Leakage Current.*

For this test the condenser should be connected, in series with a resistance and milliammeter, to a D.C. source the voltage of which is approximately equal to, but not greater than, the voltage rating of the condenser. The value of the resistance should be chosen to pass a current of 100 to 200 mA. when the condenser is short circuited.

When the circuit is first completed, the current will rise momentarily almost to the short circuit value and will then decay, rapidly at first and then at a gradually decreasing rate, till it finally settles down to a steady value. A multi-range milliammeter with switch for selecting ranges is useful so that it can be set to a high range to protect it from damage due to condenser charging current and then switched to a more sensitive range as the current decays.

The leakage current will normally fall to a value corresponding to an insulation resistance of about 10 megohm-microfarads in 1 to 5 minutes, but may take longer than this if the condenser has been out of use for a very long period.

LONDON DISCUSSION

The Chairman (Mr. G. A. V. Sowter):

Said it would be agreed that Mr. Cozens had given a most interesting and entertaining lecture. He had started from the most elementary aspect of Condensers and had become more and more technical until it was obviously necessary to study the *Journal* in order to appreciate the mathematical treatment of smoothing. Mr. Cozens had clearly demonstrated what he had done in the way of original research and also the influence of that work in practice. In the mathematical exposition on the board he had indicated that under certain conditions for optimum smoothing the sign of the capacity reactance was reversed, which meant that a choke could be used instead of a condenser. If this idea were carried to its logical conclusion suitable propaganda might be forthcoming to increase the sale of chokes as condenser substitutes, but it is feared that the " certain conditions " mentioned do not normally apply in practice.

The chairman then opened the meeting for discussion.

Mr. W. A. Beatty (Member):

" How is it possible to recognise, say by breaking open and examining, one of these low inductance condensers as a type ? One could break open an extended foil type and recognise it as such, but is there not some quick method of recognising the lug type in the improved form, and how is it possible quickly to recognise the desirable engineering features in that condenser ?

" In view of present day shortage of tin-foil and even paper it is interesting to recall that some years ago it was found desirable to make a test at the very first stage of rolling whilst the condenser was still drying. This was a test at a fairly low voltage, and it was possible to relate the low voltage test, while the condenser was drying, to the conditions normally obtained with the high voltage test after final manufacture. The idea then was to save tin foil, but at present it was also worth while to save paper. In this same connection, we had been manufacturing condensers with a length of foil wound off and measured accurately, but in the manufacture of condensers to which he had referred it was found that much better tolerances could be obtained by not measuring the length of foil at all but by counting the number of turns rolled. This was found to give better results and it also saved material. Was that method adopted in this country? It had definitely been proved to be of use from the manufacturing point of view.

" As one would expect in such a paper as this, Mr. Cozens has only dealt with the major radio applications, but the small electrolytic condenser suggested many other applications. There was an application some 35 years ago for handling toll calls on telephone exchanges. The condensers were charged on the relay system and were used for telling the trunk operator when to come in. There are numerous applications for these condensers of which Mr. Cozens no doubt has some inkling."

Mr. Spreadbury (Associate Member):

" What would be the effect if a condenser of the roll type were wound non-inductively like a resistance? "

Mr. Davey:

" Certain difficulties have been encountered from the point of surges when using dry electrolytic condensers as compared with the wet type. Will Mr. Cozens comment on this point? "

Mr. R. L. West (Associate Member):

" No mention has been made of the Mansbridge condenser. Does the power factor of the waxed paper type of condenser rise with temperature?

" Does the optimum power factor effect in a smoothing condenser apply in the case of rectified supply with a considerable harmonic content, such as would occur with a mercury vapour rectifier? "

Mr. G. L. Hamburger (Associate Member):

" Referring to the use of two electrolytic condensers in series, is it advisable to use a potentiometer to fix the centre point at mid voltage?

" Will Mr. Cozens also comment on the non-polarised type of electrolytic condenser? "

Mr. Goldsmith:

" In the case of a block electrolytic condenser, with two 500 V sections, can the two be used in series to operate at 1,000 V? Also, what is the probable cause of a short circuit in a wet electrolytic condenser?

Mr. A. Bowtillier:

" What are the respective merits of vaseline, paraffin wax and chlorinated naphthalene as dielectrics?

" Referring to the variation in resistance of electrolytic condensers of 5 to 50 megohm-microfarads, is it possible to maintain that with supplies of aluminium available in wartime? "

Mr. Ray:

"Regarding the measurement of harmonics, Mr. Cozens has mentioned the point that engineers are frequently guilty of trying out things but not publishing reports upon them. This had been done in connection with some power factor condensers and it was very useful for measuring the harmonic. The current through the condenser went up as the order of the harmonic.

"There is a point in regard to the use of a series resistance in connection with spark quenching at contacts. If there were no resistance it might be found that a sudden change of current in the condenser circuit might give rise to radio frequency interference. I have encountered this a long time ago and came to the conclusion that a small amount of resistance was necessary in order to keep down radio frequency interference. Some remarks from Mr. Cozens on this point would be useful.

"A very timely reminder has been given by Mr. Cozens with regard to A.C. rating of condensers. German manufacturers were the perpetrators because they put down a test voltage of 1,500 D.C. as 1,000 A.C., which was good mathematics but not good condenser practice.

"With regard to the contact resistance of the positive foils of electrolytic condensers, the speaker had experience of a condenser which was apparently open circuited, but by applying a good surge with a large condenser, from other sources, contact had been restored and the condenser functioned normally again and had been functioning ever since. Mr. Cozens might comment on that, as it was believed that the oxide film was preventing an intimate contact with the connecting wire.

"Since Mr. Cozens had not seen any polarisation cells in use commercially reference could be made to a French product with an ox-Iron cell, which had the polarisation type of characteristic. This condenser was referred to in some of the accounts of the French Radio Exhibition, and there was a reference to it in the *Wireless Engineer* abstracts."

Mr. R. J. Cox (Student member) referred to the fact that if a steady unidirectional voltage is applied to a reversible type of electrolytic condenser, the oxide film on the foil which is at the higher potential has a relatively high resistance, while if the polarity is reversed, this same oxide film, now at the lower potential, will have quite low resistance, the reversal apparently having no deleterious effect. Did the film disappear with reversal of polarity or was the variation of resistance with direction of applied voltage a property of the aluminium oxide or of the surface contact between aluminium and oxide?

E. A. Benwell (Visitor—A. H. Hunt, Ltd.):

"In his talk this afternoon Mr. Cozens has dealt first with mica dielectric types, then with Papers, and lastly with Electrolytics. I suggest that the fundamental reason for this sequence is that of increasing imperfection due to losses, or power factor of these main types.

"If it was possible to make Paper Condensers with the lower losses of the Mica types, it would be desirable because of space and cost factors, and these advantages would be even more marked in the case of electrolytics if the losses in these could be overcome.

"The demonstration of the desirability of power factor in Electrolytics, which was limited to the smoothing condenser in a power pack filter, only compensated for a poor choke.

"I suggest that the condenser industry should aim at the ideal of zero power factor in Electrolytic, and, indeed, all types of condensers, and press the choke manufacturers to do the same with their product."

BIRMINGHAM DISCUSSION

Mr. A. J. Mare asked at what value of current it became desirable to use a resistance in series with the condenser for spark suppression.

He considered that the user should always inform the supplier if paper condensers were required for use on A.C., because condensers impregnated with wax, and in particular Halowax, were not reliable on A.C.

Could Mr. Cozens say what was the practical maximum working voltage for an electrolytic condenser, and which gave the better power factor, plain or etched foil. With regard to the example which showed that the best power factor for a smoothing condenser was 6%, it should be pointed out that condensers for A.C. capacitor start motors should have as small a power factor as possible.

Mr. F. H. Alston (Associate) asked what was the cause of corrosion spots on the outside turns of an electrolytic condenser. Was it the effect of air or the heat of the filling wax? Also what was the cause of loss of capacity in wet electrolytics?

Silvered mica condensers had been known to fail due to their inability to carry appreciable R.F. currents in oscillator circuits. Could not the silver film be made thicker or backed up with foil? Was the silver deposited chemically or by electronic means?

Mr. Alston understood that some ceramic materials had permittivities of 100 to 300. Could not these materials, finely divided, be used to coat paper and make a condenser comparable in size with an electrolytic?

In view of the naturally high contact resistance of aluminium, would not some other metal be preferable for use in paper condensers.

Mr. A. Medley (Associate) asked if the oxygen liberated by electrolysis in an electrolytic condenser, during use, continued the film-forming process and whether the hydrogen would tend to destroy the oxide film.

Mr. G. R. Griffiths remarked that the making of lug type condensers with an inductance as low as that of the extended foil type was most interesting and asked if the lugs should be inserted at the mid-point of the roll or would it be as good to put them both at one end.

Mr. G. F. Lucas asked what tests were applied to reduce to a minimum the faults which occurred in service.

Mr. K. Shaw referred to the analysis of the smoothing circuit and suggested that the optimum power factor obtained actually applied to the condenser and load in parallel.

REPLY TO LONDON DISCUSSION

Replying first to Mr. Ray's point, Mr. Cozens said he quite agreed that radio interference was likely to be caused when a condenser was used for spark quenching without a series resistance, but, unfortunately, when dealing with heavy currents, the spark quenching effect of the condenser was lost if any appreciable resistance were included in series with it. He had known of a case where a switch carrying 10 to 15 A had been fitted with a condenser which very considerably reduced sparking at the contacts, but about 6 ins. of 26 S.W.G. Eureka wire in series with the condenser had completely spoiled the effect of the condenser. It had, therefore, been necessary to specify that, in this instance, the condenser should be mounted close to the switch and not at some remote point which would have necessitated the use of long connecting leads.

With regard to contact resistance, if it was a dry type electrolytic condenser, much depended on the manner in which the external terminals were connected to the condenser foil, but generally speaking, the oxide film explanation was the true one.

In answer to Mr. Spreadbury, Mr. Cozens pointed out that the effect, if a condenser of the roll type were wound non-inductively like a resistance, would be to produce a condenser of a very low inductance. Although physically it was not the same, electrically, it was similar to what was being done in practice, each element of current being made to follow a path such as was obtained in a non-inductively wound resistance.

Replying to Mr. Beatty, the speaker stated that as far as he knew, reputable condenser manufacturers produced their goods in the manner suggested in the Paper, and one could feel satisfied if a condenser was opened and the lugs were found reasonably near together, preferably in the middle of the unit. If they were, then one would get a similar effect to that of a non-inductively wound resistance. That was all it was really necessary to look for if a condenser was opened.

With regard to testing the units before impregnation, he was unable to answer for the industry as a whole ; he could only say that in the works with which he was associated, that practice was adopted, as was also the method mentioned of controlling the capacity by the number of turns of foil rather than by the length. In the vast majority of cases the method of counting the turns was adopted.

Mr. Davey should note that dry electrolytic condensers were made which were claimed to be equally surge-proof and were intended to act in exactly the same way as wet electrolytic condensers. It was probably the fact that the dry electrolytic condensers did not stand up to that treatment quite so well as the wet type, but, generally speaking, the dry electrolytic condenser could be made to withstand a surge up to about 600 volts with the working voltage of the condenser at 500 volts. If the surge was more than that, then he did not think the dry type would be very happy. The simplest thing to do was to use two condensers in series when surges of more than 600 volts were likely to be encountered. This did not mean that two 500-volt condensers in series could be rated at 1,000 V., but certainly 800 V. and possibly 900 V. would be safe. The two condensers should, of course, be of the same type and capacity.

The Mansbridge condenser had an impregnated paper dielectric, while each electrode consisted of a layer of fine metallic powder supported on a layer of paper. The disadvantage of this type of condenser, was the high resistance between the metallic particles which caused the condenser to have a high power factor.

Mr. Cozens had not mentioned this type of condenser in his Paper because it was obsolete and very few remain in use.

In answer to Mr. West's further point, Mr. Cozens pointed out that the power factor of a paper dielectric condenser, might increase or decrease with increasing temperature, depending on the actual value of the temperature and the frequency of the applied voltage. This is illustrated by Fig. 12.

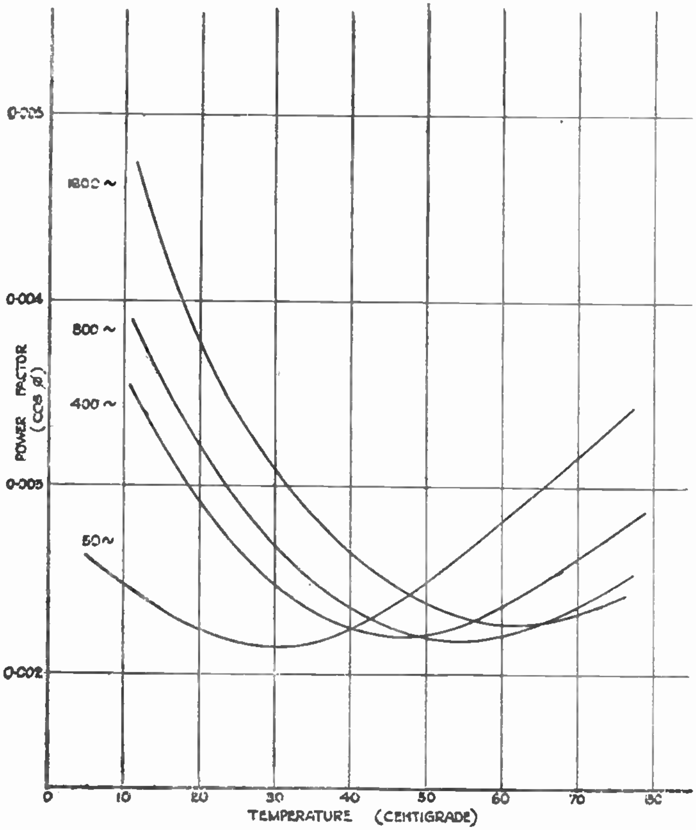

Fig. 12.—Typical variation of power factor with temperature and frequency for a paper dielectric condenser.

Mr. Cozens indicated that he has only recently started on the theory which he had demonstrated during the course of the Paper, and he had not yet had time to study anything in connection with mercury vapour rectifiers. The effect was certainly a function of frequency and a high harmonic content would probably mean a smaller value for the optimum power factor.

Replying to Mr. G. L. Hamburger, Mr. Cozens said it was not generally desirable to put a potentiometer across condensers, for two reasons. One was that the voltage distribution would tend to balance up automatically; and secondly, for the potentiometer to be effective each arm would have to be of a resistance considerably lower than that of the condenser, and since he was dealing with condensers with low resistance, the potentiometer would take a heavy current and have to be rated accordingly. Generally speaking, he did not think it would be a practicable proposition.

J. H. COZENS

With reference to the reversible or non-polarised type of electrolytic condenser, he could not go very deeply into that because it was almost another section, but very briefly, the effect could be considered as that of two condensers connected in series with opposite polarity, as shown in Fig. 13a.

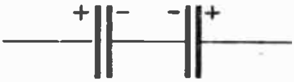

Fig. 13a.—Two electrolytic condensers connected "back to back" for operation as a single reversible or non-polarised unit.

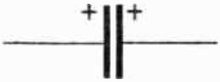

Fig. 13b. — Equivalent effect produced by winding the two positive foils in one unit and omitting negative foils.

In practice the condenser was made with two positive foils, as shown in Fig. 13b, the negative foils being omitted since their only function was to make contact with the electrolyte.

Mr. Hamburger asked whether it would not have a very detrimental effect on the power factor, because one condenser was always conductive.

Mr. Cozens agreed that it might tend to increase the power factor, but in practice the effect was negligible.

Mr. Gardiner asked whether it was not a fact that with such a method the condensers would be made of tantalum and not aluminium.

Mr. Cozens replied that very few condensers had tantalum electrodes. Practically all electrolytic condensers had electrodes of aluminium.

Mr. Goldsmith's proposal could be carried out provided that the two were isolated and did not have a common negative or positive connection. The two sections should have the same nominal capacity and the applied voltage should not exceed 900.

A short circuit in a wet electrolytic condenser, meant that something was radically wrong. There might be a mechanical defect such as the displacement of the central electrode, or the level of the electrolyte might have fallen sufficiently to expose the top of the electrode. In the latter case, corrosion would tend to occur at the point where the electrode came through the surface of the electrolyte, the oxide film would be destroyed and a short circuit would develop. This was the most frequent cause of failure after several years of service.

Replying to Mr. Bowtillier, Mr. Cozens pointed out that supplies of aluminium at the present time were not too bad, although the aluminium obtainable to-day, was not quite as good as it used to be. Of the three impregnants mentioned, petroleum jelly was undoubtedly the best for impregnating paper dielectrics.

Resistance was usually higher than with the other two, and since water absorption was lower, deterioration from this cause was much less likely to occur. Reliability at high working voltages was greater than with paraffin wax or with chlorinated naphthalene.

Paraffin wax could be made to give a slightly higher breakdown voltage under certain conditions, than petroleum jelly, but this was of no practical value in service, since it was outweighed by the other advantages of petroleum jelly.

Chlorinated naphthalene gave about 50% greater capacity for a given volume than the other two materials, but its breakdown voltage was lower.

Its chief use, therefore, lay in the production of condensers for voltages up to about 200 where space was limited. The high melting point of chlorinated naphthalene was sometimes useful for high temperature working.

Mr. R. J. Cox should note that the precise mechanism of the variation of resistance of the film with reversal of polarity was not known, but certainly the film was not removed from that pole of a reversible condenser which was made negative. This was apparent from the fact that A.C. measurements showed that the electrolytic condenser having two formed foils had half the capacity of a condenser with one formed and one unformed foil, other details of construction being unchanged.

The phenomenon did not appear to be a property of the aluminium oxide as such, but rather of the electrolyte-oxide-metal combination, and there was considerable room for research in that direction.

With regard to Mr. Benwell's remarks, the statement that the optimum power factor was greater than zero was made during the discussion of smoothing condensers and was not intended to apply to any other application.

The most important quantity to specify in connection with a smoothing condenser was its impedance, and for a given value of impedance, the higher the power factor the better the smoothing, whatever the quality of the choke.

If a particular capacity was specified, then for that given capacity there would be greatest smoothing when the condenser power factor had a certain optimum value which was greater than zero. It was agreed that in this case the optimum value of condenser power factor decreased when the choke factor decreased, but since a choke with zero power factor was a physical impossibility, it followed that the optimum power factor for a smoothing condenser could never be zero.

REPLY TO BIRMINGHAM DISCUSSION

In reply to Mr. Mare, Mr. Cozens said there was no value of current at which the conditions showed a marked change. Most of his experiments had been made with currents of 5 to 20 A, and with these a resistance had always been found to be detrimental. In the case of relay contacts carrying only a few milliamperes, a series resistance would probably prove useful.

The practical maximum working voltage for a single unit electrolytic condenser was 500 to 550 V. Higher voltage condensers could be made in the laboratory, but their power factor was high. In practice voltage ratings above 500 were obtained by series connected units.

Plain foil would give a lower power factor than etched foil, other materials being unchanged, because the greater surface area resulted in lower electrolyte resistance.

The analysis of the smoothing circuit to show that there was an optimum power factor did not imply that this condition was valid for application other than smoothing circuits. Also the figure of 6% applied only to the particular circuit used for the example It was agreed that motor-starting condensers should have the lowest possible power factor.

Replying to Mr. Alston, Mr. Cozens thought the corrosion was not likely to be due to heat from the wax, but rather to chemical impurities in the wax or excessive moisture absorbed from the atmosphere. Loss of capacity in wet electrolytics was due to either excessive ripple, reversal of polarity or loss of electrolyte.

Silvered mica could be backed with foil, but efforts were being made to produce thicker silver films. The silver was usually applied in the form of an organic compound which was subsequently decomposed by heat, leaving metallic silver.

The idea of coating paper with ceramic powder of high permittivity was attractive but, at present, the practical difficulties were considerable.

Aluminium foil was not found to give trouble in paper condensers due to its high contact resistance, except in a few special applications, and for these, tin foil was normally used.

Mr. Medley was correct in suggesting that oxygen produced by electrolysis continued the film-forming process in an electrolytic condenser during use. The hydrogen did not destroy the film.

In answer to Mr. Griffiths, Mr. Cozens said that low inductance would be obtained by placing both lugs at one end of the roll, but if they were both placed at the mid-point the effective series-resistance would be reduced in addition.

Answering Mr. Lucas, it was explained that leakage current, capacity and power factor were measured on every unit, both during manufacture and after completion. Raw materials were tested to a very high degree of accuracy, as little as one part in a million of certain impurities being sufficient to reject them.

Mr. Cozens agreed with Mr. Shaw that the optimum power factor for the smoothing condenser really included the effect of the load in parallel with the condenser, and pointed out that, for simplicity, the effect of the load had been assumed to be negligible in the mathematical analysis. This assumption could be shown to be justified for normal values of load, and the demonstration had illustrated this point.

Proposing a vote of thanks, Mr. H. A. Hartley (Member) stated that Mr. Cozens was a very valued colleague in condenser standardisation, for if there was one thing the condenser industry had to face it was the eternal problem of having to " carry the baby " for designers' mistakes. That was probably due to the fact that in the past, designers had been trained to consider capacitor as a dimension and nothing else. Condenser makers were often told that their products were no good because they broke down, but Mr. Cozens would be able to mention numerous cases in which he had investigated the conditions and found they were not what the designer had said they would be. Therefore, perhaps the most valuable part of the Paper was that it impressed on circuit designers the need for calling in the condenser manufacturer and collaborating with him. There were many pitfalls to which the condenser manufacturer usually knew the answers, and therefore, designers should get together with the condenser manufacturers in the early stages.

Not only had Mr. Cozens given circuit designers and users of condensers a large amount of material, but also the industry as a whole, and he was to be thanked for the able manner in which he had debunked the power factor problem ; it was more a case of set design. Under conditions where temperatures became subnormal, the p.f. problem loomed very large, but after a considerable amount of work it had been agreed with the Services to specify performance of a condenser in terms of impedance, because that gave a much truer picture of what happened in the circuit than taking into consideration what appeared to be fantastic power factors which really had no effect on the performance in service.

Replying to the vote of thanks, Mr. Cozens expressed his appreciation, and said he hoped his audience had enjoyed the Paper, because the preparation of it had given him a great deal of pleasure. If the Paper had proved of interest, then he was very well satisfied and very gratified indeed that so many should give up a fine afternoon to listen to it.

The

British Institution of Radio Engineers

GRADUATESHIP EXAMINATION.

PASS LIST—NOVEMBER 1942.

Success in the examination does not, of itself, obtain membership.

Passed entire Examination with Distinction

Leonard W. Blick (S.)	London, N.11

Passed entire Examination with Credit

William D. Hamer	West Kirby, Ches.

*Pass List.**

Arthur G. Bassett	Guildford, Surrey
Lionel Kow (S.)	Hayes, Middlesex
Harry McGuffin, B.Sc., A.M.I.E.E.	Belfast
Frank M. Middleton	Crewe, Ches.
Jack S. Nicklin (S.)	Crewe, Ches.
Kenneth D. Reed (S.)	Potters Bar, Middx.
David Rich	Maidenhead
Rokus Schelling (S.)	South Africa
Laurence J. Snell (S.)	Stourpoint-on-Severn
Ronald D. Watts	Cardiganshire
Starkie Whittam (S.)	Horsham, Sussex

* This List also includes Candidates who are exempt from, or who have previously passed, a part of the Examination and who have now passed the remaining subjects.

The Following Candidates Passed Part 1 only

John A. Delany (S.)	Birmingham
Charles R. Leslie (S.)	Farnborough, Hants.

The Following Candidate Passed Parts 1 and 2 only

William A. Jones (S.)	Fairlie, Ayrshire

The Following Candidate Passed Parts 1, 2 and 3 only

Eric A. J. Rogers (S.)	Romsey, Hampshire

The Following Candidate Passed Parts 2 and 4 only

Francis R. Fallon (S.)	Lennoxtown

The Following Candidates Passed Part 3 only

Albert P. Cartwright	Aberdeen
Paul Erdos (S.)	Aberfeldy, Perthshire

The Following Candidate Passed Parts 3 and 4 only

Herbert J. Selves	Eltham, London

The Following Candidates Passed Part 4 only

Edwin G. Gamble	Barnehurst, Kent
Desmond Sherley-Price (S.)	Bournemouth

THE Brit.I.R.E. RADIO SERVICING CERTIFICATE EXAMINATION

Pass List

Rokus Schelling (S.)	S. Africa
Richard W. Hollingsworth	Burton-on-Trent
William J. Smith	Whitton, Mdx.
Frederick J. Wixley	Watford, Herts.

AWARD OF PRIZES

The General Council considered the annual report of the Education and Examination Committee on February 5th, 1943, and approved the following awards to the most successful candidates in the two Graduateship examinations held during 1942 :—

PRESIDENT'S PRIZE

(This Prize is awarded to the Candidate who has proved himself the best candidate among those who presented themselves for the Graduateship examinations of the Institution held during the year).

LEONARD WILLIAM BLICK (Registered Student)
London, N.11

THE MOUNTBATTEN MEDAL

(This Medal is awarded to the Candidate who has proved himself the best Candidate among those of the Royal Navy, Army or Air Force, who have presented themselves for the Graduateship Examination of the Institution held during the year.)

LEONARD WILLIAM BLICK (Registered Student)
London, N.11

THE L.R.C. PRIZE

(This Prize is awarded annually to the Candidate who takes second place in order of merit among those who have passed the Graduateship Examination of the Institution held during the year).

JOHN POLLARD, B.Sc. (Associate) Liskeard, Cornwall.

EXAMINERS' REPORT

A report on the May 1942 examination was given in the September/November 1942 *Journal*. The following reports relate to the November 1942 Examination :—

Part 1 (*Heat, Light and Sound*).—Less than half the number of candidates entering for this section succeeded in gaining a pass mark. The weakness appears to lie in preparation for the examination and there is a tendency to memorise a formula, or a definition, rather than to understand a principle. Candidates should see if the results they obtain are reasonable. For example, one candidate in Question 1 obtained a temperature of 40,000° C and left it without comment; the inference being that he could see nothing absurd about it.

In dealing with refraction, all candidates indicated their knowledge of " the angle of incidence," but only three candidates thought it had any effect on the illumination, and of those, only one knew how to find the cosine.

All candidates showed some weakness on the subject of sound and there was a considerable tendency to separate theory from practice.

Part 1 (*Electricity and Magnetism*).—The general results were poor, insufficient attention being given to detail; many candidates confusing terms and units, e.g., current for voltage.

A common fault was misreading or not closely reading questions, leading to omission of details clearly asked for and the introduction of irrelevant details.

Part 3 (*Radio Engineering*).—In general, the Papers were of a better standard than hitherto. Marks gained were higher, partly due to the fact that the "effective" number of questions had been reduced by about 20 to 30 per cent. from previous papers, so that more time was available per question, and also because of a better quality of entrant in general.

The Paper still demonstrated, however, that Candidates begin to flounder if some general questions are asked involving rectifier systems of types not used for broadcast reception methods, of using transmitting valves or circuit problems which need some knowledge of vectors to obtain answers by short-cut methods.

The results show that Candidates' study is not sufficiently wide over the field of Radio Engineering, perhaps because the present syllabus of teaching may ignore the " heavy " side of the business.

Part 4 (*Radio Receiver Design and Practice*).—In general, candidates taking this Paper exhibit a far too superficial knowledge of receiver design and practice. The questions are such that even the non-specialist student should be able to give answers of a sort, but the examiners look for deeper knowledge, indicating that the candidate has qualifications appropriate to the designing, rather than the repairing, side of the industry.

On the whole, candidates chose their questions and used the available time to good advantage.

Certain candidates tried to introduce mathematics wherever possible, but showed so many inaccuracies that it would have been better for them to leave it out. The examiners are not impressed by mathematics which is not really germane to the question, particularly where mistakes occur in it.

On the other hand, certain questions really required mathematical explanations, which were often not forthcoming.

Radio Transmission.—The general standard of these papers was good, but in some cases candidates would have obtained better marks had they read the questions more carefully.

More attention should be paid to Regulation 9 of the regulations governing the examinations and prospective candidates are reminded that marks will be lost due to defective writing and spelling.

Television.—In general over the past four examinations the standard exhibited by candidates has been conspicuously poor, and in almost all cases the treatment of the questions has indicated only a very elementary knowledge of the subject. In addition, many marks have been lost because candidates fail to check their own answers to verify that they have in fact answered the question, and have avoided foolish and obvious mistakes.

There was an apparent shyness of questions involving Cathode Ray Tube circuits, and the treatment of the Emitron circuit details in question 9 were rather weak.

At the same time some consideration must be shown to the fact that at the present time the opportunities afforded for a candidate to have any practical experience of the problems involved are necessarily small, and every endeavour has been made to avoid penalising an answer showing lack of practical television experience, provided the candidate shows genuine basic knowledge.

The general impression left by the Papers is, however, that the syllabus is not understood ; this accounts in some respects for carelessness, but to a much greater degree is due to inadequate preparation for the examination.

Forthcoming Examinations

The Graduateship Examination was held on May 14th and 15th. The November, 1943 examination will be held on November 19th and 20th, and applications must be lodged not later than September 30th.

Copies of papers set in the May and November, 1942, examinations are available at 2s. 6d. per copy, post free, or 3s. 6d. the two sets. Papers set from 1926 to 1940, inclusive, are now out of print, and it is not intended to reprint them.

The

British Institution of Radio Engineers

NOTICES

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Obituary

LORD HIRST OF WITTON. We regret to record the death of Lord Hirst on January 22nd, 1943, in his 79th year.

An Honorary Member of the Institution, Lord Hirst was Patron of the Institute of Wireless Technology for many years and held this office until fusion with the British Institution of Radio Engineers.

The church of St. Martin in the Fields, London, was packed for the memorial service on January 27th, by Representatives of Institutions, Societies, and Associations with which Lord Hirst had been prominently connected and of course, many Representatives from the General Electric Company which he founded.

LORD GAINFORD. We also regret to announce the death of Lord Gainford, P.C., also Patron of the Institution from 1936 to 1940.

The late Lord Gainford, was the first Chairman of the British Broadcasting Company, 1922-1925, and subsequently the first vice-chairman of the Corporation. He was raised to the Peerage in 1917 after having sat in the House of Commons for 24 years as a Liberal. During his Parliamentary career he held the appointments of Post Master General, President of the Board of Education and Chancellor of the Duchy of Lancaster.

He died at the age of 83 years at Hedlam Hall, Darlington.

Mr. RICHARD HAZLETON.—The Institution of Production Engineers have also suffered a severe loss in the death on January 26th, 1943, of their General Secretary. A testimony to his services to the Institution has recently been received from Sir Ernest J. H. Lemon, Vice-President L.M. and S. Railways.

Formerly M.P. for North Galway 1906-18 and North Louth 1911, Mr. Hazleton devoted himself entirely to the work of the Institution of Production Engineers from 1929 until his sudden death.

The Institution's Change of Address

Members will help by making the Institution's change of address known and thus save delay in the acknowledgment of letters and enquiries. Although the Post Office are readdressing communications, two or three days delay is sometimes experienced. Members should therefore note and make it known that all communications should be addressed to the new headquarters.

Radio Trades Examination Board

Representatives of the Radio Manufacturers' Association, the Scottish Radio Retailers' Association and the Radio and Television Retailers' Association attended a Meeting of the Board on the 16th February.

The Institution was represented by Mr. S. A. Hurren, M.C. (Fellow), Mr. J. DeGruchy (Member) and Mr. R. L. West, B.Sc. (Associate Member).

The Board is to be incorporated and the syllabus and regulations of the new Radio Servicing examination will be prepared by a Technical Committee appointed by the Board and comprising two representatives from each Association and the Institution.

The first examination under the auspices of the Board will take place in November 1943 and like the Brit.I.R.E. Servicing Certificate Examination, which the Board's examination will replace, will comprise both written and practical examinations.

Post-War Planning

Although post-war planning has not been a prominent feature in the Institution's work until recently, more attention is being given to the subject under the ægis of the Professional Purposes Committee. This Committee has received many suggestions and it is proposed to call a select meeting of about 30 members in the near future in order to discuss these suggestions, with a view to holding an open meeting for a discussion on the subject.

Members who wish to place views before the Committee should address their contributions to the Secretary, and their remarks should, of course, be constructive and be solely concerned with the radio engineering profession.

Year Book

The next issue of the Year Book will be available about the end of June. Members of all grades will considerably assist by advising the Secretary, as soon as possible, of any changes in their private addresses, and in the case of members in the Services, of any recent promotion.

Imperial College Union

Details have been received of the 8th Annual Report of the Vacation Apprenticeship Scheme for students of the Imperial College of Science and Technology.

During the session 1941/2 there were 340 registrations for Works experience in the summer of 1942, and it has been found necessary to extend the Register of firms willing to accept students. The previous peak year was 1939, when 228 students registered. It has now been decided that prospective students who are qualified for admission to a Second Year Course shall be offered facilities for obtaining Works experience during the Summer Vacation before joining their Colleges.

It is interesting to note that two Radio Engineering establishments are included in the Reports received from firms. There has been an upward trend in payments made to the students by the firms :—

5 students received between £40 and £50 each
8 students received between £30 and £40 each
32 students received between £20 and £30 each
118 students received between £10 and £20 each
60 students received between £4 and £10 each

Included in the list of firms who co-operated in the scheme during the summer of 1942 are :—

Messrs. Callender's Cable & Construction Co., Ltd.
The Cambridge Instrument Co., Ltd.
Messrs. E. K. Cole, Ltd.
The Electrical Apparatus Co., Ltd.
The English Electric Co., Ltd.
Messrs. Ericsson Telephones, Ltd.
H.M.V. Gramophone Works.
Messrs. Igranic Electric Co., Ltd.
Messrs. Kodak, Ltd.
Messrs. Kolster Brandes, Ltd.
The Metropolitan-Vickers Electrical Co., Ltd.
The Mitcham Works, Ltd.
The Mullard Wireless Service Co., Ltd.
Messrs. Rediffusion, Ltd.
Messrs. Standard Telephones & Cables, Ltd.

The Report concludes :—

"It is considered that the privilege of obtaining practical experience with Industry during the long vacations is of very great value to these young students, and is likely to have a marked effect on their professional progress. Moreover, the reaction of the students and the growing popularity of the Scheme indicates that the former appreciate the value of the experience opened up to them."

Previous Issues of Journals

In order to save correspondence, will members please note that apart from the copies which may be borrowed from the library, back copies of the Institution's Journal and proceedings prior to July 1942 are no longer available.

Bound copies of previous Journals are also now out of print with the exception of a few copies of the bound Journal for 1939-40, which are available at 12s. 6d. per bound copy, post free.

Annual Election of Officers, Council and Committees.

In accordance with Article 32, the Council will, in June next, send to each corporate member a list of duly qualified persons whom they nominate for the vacancies about to occur in the offices of Ordinary Members of Council. "After the issue of the

Council's list, and not later than twenty-one days after the date of such issue, any ten corporate members may nominate any other duly qualified person to fill any such vacancy by delivering such nomination in writing to the Secretary, together with the written consent of such person to accept office, if elected."

The Council will also be pleased to receive nominations and/or applications from members qualified to serve on Standing Committees. In this connection, members and Associates should refer to pages 175-6.

Article 29 provides that half the Ordinary Members of Council shall retire in rotation, and notice of the six members who remain on Council for 1943-44 will be circulated to Corporate Members in June.

Library Catalogue

A revised catalogue of the Institution's Library, with index, will be available at the end of July. In view of paper supplies, copies will not, for the duration of war, be circularised to members, but a copy may be obtained on application to the Librarian.

Books for Prisoners of War

Requests are still being received from prisoners of war for text books and reading material on Physics and Radio Engineering (all branches). The Secretary will be pleased to receive from members copies of books or old copies of radio journals for re-despatch to prisoner of war camps.

Several member prisoners of war have organised training classes in their camps. It is not possible, of course, to send some of the latest English text books, but nearly all the literature published prior to 1939 will be permitted by both English and German Censorships.

The

British Institution of Radio Engineers

SOME INDUSTRIAL APPLICATIONS OF ELECTRONICS

by

J. H. Reyner, B.Sc., D.I.C., A.M.I.E.E.

Paper read before the British Institution of Radio Engineers on Friday, February 19th, 1943.

Industry is beginning to realise that equipment containing valves and similar electronic devices is no longer to be regarded with suspicion. Valves themselves are more reliable, but a point of greater significance is the improved design of the associated circuits, in connection with which sound engineering principles are now being brought to bear. The conditions are quite different from those in a radio receiver where first cost is of considerable importance. The price of electronic equipment is usually small in comparison with the process which it serves and a failure may well cost the user many times more than the original purchase price of the instrument.

This difference is being appreciated by designers who are, in consequence, adopting ample factors of safety in their designs. More attention is also paid to-day to the influence on performance of the inevitable changes in circuit constants due to ageing, particularly as regards the valves. Development along these lines has contributed more than anything to the increasing confidence which industry is disposed to place in this class of equipment. As this confidence grows, greater and greater opportunities are being afforded for the ingenuity of the electronic engineer and provided he keeps faith with the purchaser there is every reason to believe that electronics will play an increasing part in the industrial world.

It is proposed in this paper to describe some of the applications which have fallen within the author's experience. The descriptions will be on broad outlines rather than in the form of detailed analyses for obvious reasons.

Negative Feedback

One of the developments which has assisted most within recent years is the use of the inverse feedback principle. This now familiar technique involves transferring a portion of the output of an amplifier back to the input in such a sense as to oppose the original input voltage. This will reduce the effective amplification but it has the advantage that if the conditions are suitably chosen the effective amplification of the whole arrangement is simply $1/\beta$ where β is the *feedback factor* or the proportion of the output which is fed back to the input.

Now β is substantially a constant, so that the gain of the amplifier is also constant irrespective of changes in the internal parameters. For example, a valve may change its characteristics substantially, due to ageing, without affecting the results. Appreciable changes in the values of the components have a similarly negligible influence on the performance. While this compensation for internal variations obviously cannot apply indefinitely there is nevertheless a marked improvement in the stability. A feedback amplifier may, in fact, be considered as a device having a known and constant performance and this removes one of the major arguments against the use of valves for control equipment.

The performance indeed is good enough to warrant the inclusion of valves in measuring instruments. A particular example of this is the feedback voltmeter illustrated in Fig. 1. This is an arrangement using a two-stage amplifier with a substantial measure of negative feedback. The output from the amplifier is rectified and passed through a meter, and with this instrument it is possible to measure voltages ranging from one millivolt to 100 volts, employing a conventional 10-1 multiplier so that the range can be covered in five steps.

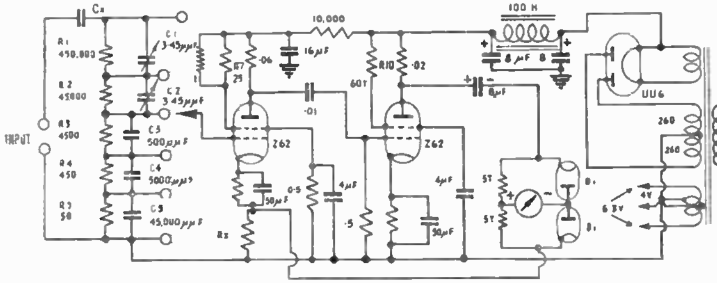


Fig. 1.

This particular instrument is effective over a range of 50 c/s. to 100 kc/s. Outside these limits the performance becomes unreliable because the phase of the feedback changes. The independence of internal constants only holds good so long as the feedback is exactly in opposition to the input voltage, and with any amplifier there are limits of frequency outside which appreciable phase shift results. If the phase shifts more than 90 degrees a component of the feedback becomes positive and continuous oscillation may ensue. To avoid this, the amplifier should be designed so that the gain falls off rapidly ouside the working range, becoming less than unity at the frequency which corresponds to 180 degrees phase shift.

This condition is achieved with a simple single stage amplifier, but with two or more stages the use of filter networks may be necessary to accelerate the loss of gain beyond the cut off point.

A further use of feedback which may be mentioned in passing is in the control of the source impedance of the output stage. Voltage feedback tends to maintain the voltage constant which is a condition associated with a low internal impedance. Current feedback tends to a constant current condition which is equivalent to a high internal impedance. By a mixture of both forms any desired source impedance may be obtained.

Vibration Analysers

The need for analysing a complex wave is often encountered in engineering practice, more particularly as applied to vibrations in machinery. The vibrations are first translated into electrical currents by means of a piezo-electric or other suitable pick-up. The resulting current, suitably amplified, is then passed through a suitable selective network by means of which the frequency and magnitude of each of the components is ascertained.

The usual method employs a crystal gate, tuned to a frequency such as 50 kc/s., as the selecting mechanism. A local oscillator is then used to heterodyne the incoming signal, producing beats with each component in turn. This method is well established and accurate.

The feedback principle, however, affords an alternative method which is rather simpler and equally effective unless a high degree of discrimination is required. With this arrangement an amplifier is constructed capable of being tuned quite sharply to any frequency within the range of the vibrations concerned. Thus as the control is operated each component is selected in turn, the amplitude and frequency being quickly determined.

The amplifier does not employ conventional tuned circuits, but is a resistance-capacity coupled system with substantial negative feedback applied through a bridge network which is frequency dependent, as shown in Fig. 2. Normally this bridge is out of balance so that an appreciable amount of voltage is fed back and the gain of the amplifier is considerably reduced as a result. At the frequency of balance, however, the output from the bridge is very small, and little or no feedback is obtained. The amplifier is then able to develop its full normal gain.

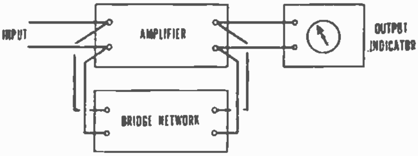


Fig. 2.

The arrangement thus has the properties of a tuned network giving maximum response at the frequency for which the bridge is balanced. If the bridge network is made variable it is possible to alter the response of the amplifier over a wide range, thus providing a sharply selective amplifier of variable tune. The arrangement can be made up in very portable form. Its main disadvantage is that the selectivity is not very good, a typical response curve being shown in Fig. 3.

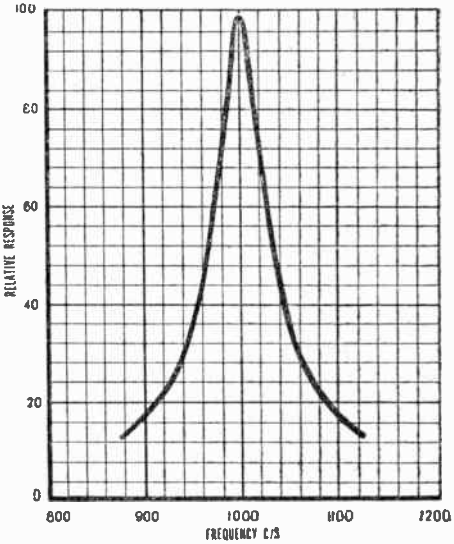


Fig. 3.

The discrimination can be improved by introducing a little positive feedback which provides a reaction effect, but this makes the gain of the system indeterminate. as with any reaction system. and requires the provision of some calibrating source to enable the performance to be checked prior to any series of measurements.

Feedback Oscillators

If the positive feedback is made sufficient the circuit will oscillate at the frequency to which the network is tuned. This provides an oscillator which, with suitable precautions, can be made very stable. It is desirable to incorporate a diode or similar circuit to limit the amplitude of the oscillation to a value within the operating range of the valves rather than relying on the inherent self limiting action of the valves. Fig. 4 shows an oscillator of this type covering a frequency range of 5 c/s. to 15,000 c/s. with a stability of 0·01 per cent. and a reading accuracy of the same order.

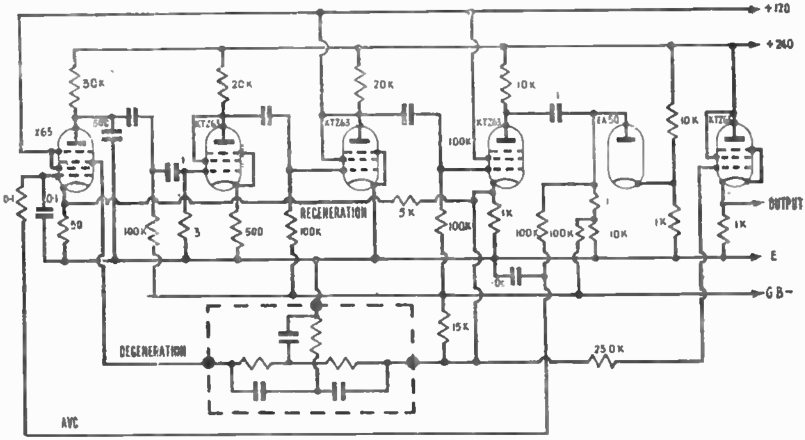
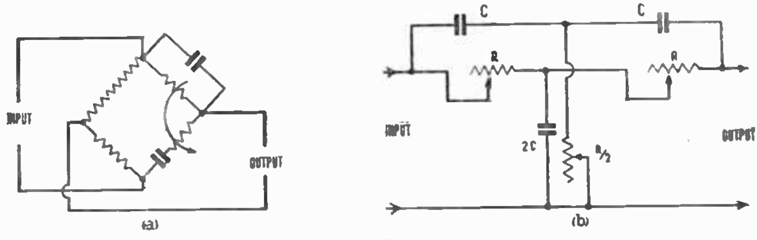


Fig 4.



(a)

(b)

Fig 5.

The form of bridge network used to control the feedback is as shown in Fig. 5(*a*). The arrangement of Fig. 5(*b*) is a three terminal equivalent of the more conventional circuit, and is used because it permits one side of the circuit to be earthy both on the input and output sides.

This involves a 3-gang potentiometer and the stability and performance of the whole circuit is largely governed by this component. The ordinary forms of construction are not wholly adequate, and it is often found that the electrical performance is several times better than the mechanical construction permits. This, however, is a practical difficulty which will be overcome in due course.

Stable Oscillators

The provision of stable sources of frequency is another requirement of modern industry. Prior to the war the mains supply was considered as sufficiently stable for many purposes. Where a mechanism such as a tachometer had to be driven at a known speed it was convenient to use a synchronous motor, driven, if necessary, through suitable gearing, and to rely on the frequency of the mains being within a small fraction of its rated value. This is no longer true, and the frequency may well vary ± 0·5 c/s. Moreover, the precision of modern measuring instruments is calling for closer tolerances than before, so that an accuracy of 0·01 per cent. is no uncommon requirement to-day.

A tuning fork, electrically maintained, is often used in such circumstances. Tuning forks, however, are far from being the precision standards that they are popularly supposed to be. With suitable precautions they are excellent, but with any crude system the influence of the maintaining circuit on the fork is not negligible, and the temperature coefficient of even an Invar fork is much greater than is commonly supposed. For precision work Elinvar has to be used, which is not only expensive, but in very short supply.

An oscillator constructed on the same principles as the variable oscillator described in the previous section can be made to give stability far greater than the average fork. A circuit recently constructed in the author's laboratories had a temperature coefficient of thirteen parts in a million per degree centigrade without any special provision for temperature compensation. With a temperature compensated chamber it is probable that a precision of something like five parts in a million could be attained. It is worth noting that the temperature coefficient of an electrically maintained fork against which this oscillator was checked was 140 parts in a million per degree C.

Another form of stable circuit made up in the author's laboratories uses a plain inductance-capacity oscillator. The tuned circuit here was designed to have a reasonably high Q (of the order of 60). Such a circuit can be constructed without serious difficulty for frequencies between 2,000 and 3,000 c/s. The frequency so generated can then be stepped down, by multi-vibrators or a regenerative modulator, to a convenient sub-multiple, finally arriving at 50 c/s. or any other desired frequency. A typical example

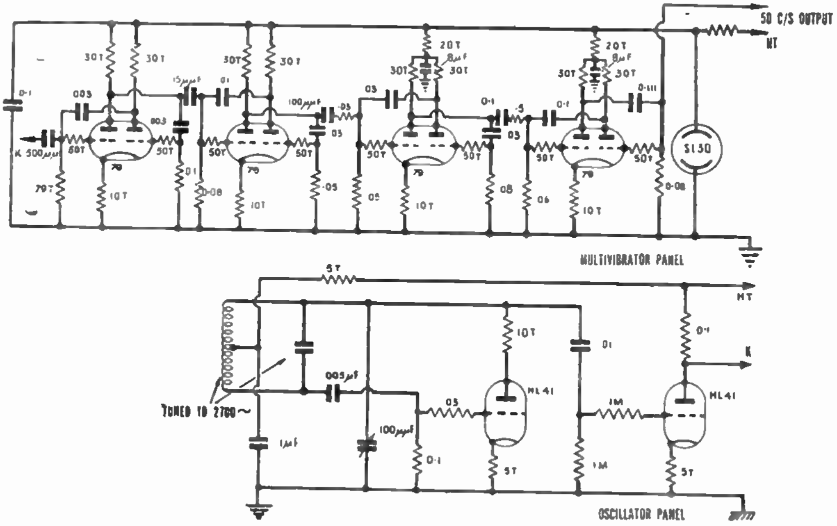


Fig. 6.

of this form of construction resulted in a stability of ten parts per million per degree C. This was with a measure of temperature compensation obtained by using a mixture of condensers having positive and negative temperature coefficients for the tuning, but no further precautions were taken. The circuit is shown in Fig. 6.

A particular development of this technique was applied to a set-up for which a series of frequencies was required in the region of 100 c/s, differing by exactly 1 c/s. each.

Clock Timing

Another development in connection with accurate timing is that of assessing the gain or loss of a watch or clock. Hitherto the only method was to observe the timepieces for a long period by comparison with a standard. This is a lengthy business, becoming longer the closer the accuracy required.

Modern electronic technique enables the results to be obtained in a few seconds. A quartz crystal is used to generate a standard frequency and this frequency is then sub-divided by multi-vibrators or other suitable technique until a frequency of the order of 60 c/s. is reached. This frequency is then utilised to drive a synchronous motor carrying on its shaft a disc with a series of projections on its periphery.

The standard rate of tick of the majority of watches made to-day is five per second (300 per minute). The beat of the watch is picked up with a microphone and suitably amplified until it can operate a mechanical device of some sort such as a presser bar which will bring a piece of paper into contact with the rotating disc.

If this presser bar is operated at a point when one of the projections on the disc is exactly vertical a mark will be made in the centre of the paper. If the next tick of the watch is correctly timed the next mark on the paper will be in the same relative position so that if the paper is caused to travel along slowly a series of dots will be obtained in a straight line running along the length of the paper.

If the watch is gaining or losing, the position of the projection on the disc will not be exactly the same at each successive tick of the watch, and the marks on the paper, therefore, will be inclined to one side or the other. The angle of travel is a direct measure of the gain or loss of the watch.

This description is admittedly brief, but it will be clear that by suitable choice of the number of projections on the disc and the speed at which the disc rotates it can be made to give the information in any desired form, and even to be applied to watches having different rates of beat.

A somewhat simpler development of the arrangement is to use a cathode ray tube in place of the rotating disc. The spot on the cathode ray tube is caused to scan vertically over the screen at a rate of something like 30 sweeps/sec., this time base being synchronised from the quartz crystal through multi-vibrators as before. The beat of the watch is amplified as previously, and is applied to the horizontal deflector plates, where it produces a complex pattern which should remain stationary if the beat of the watch is exactly correct. In practice, of course, it travels slowly up or down the screen at a rate which determines the gain or loss of the watch. The circuit of a typical set up is shown in Fig. 7.

It is also interesting to note that the form of pattern produced by the tick of the watch often gives a clue to the experienced craftsman as to whether the watch is in correct adjustment. He can tell by looking at it whether the hairspring is binding, whether the pivots are too tighly adjusted and so on. It is also worth noting that in all but the best watches there is a hunt on the beat causing the successive images to vary in position on either side of the mean value. In the case of the cathode ray device the image dithers up and down, superposed on a slow vertical transit.

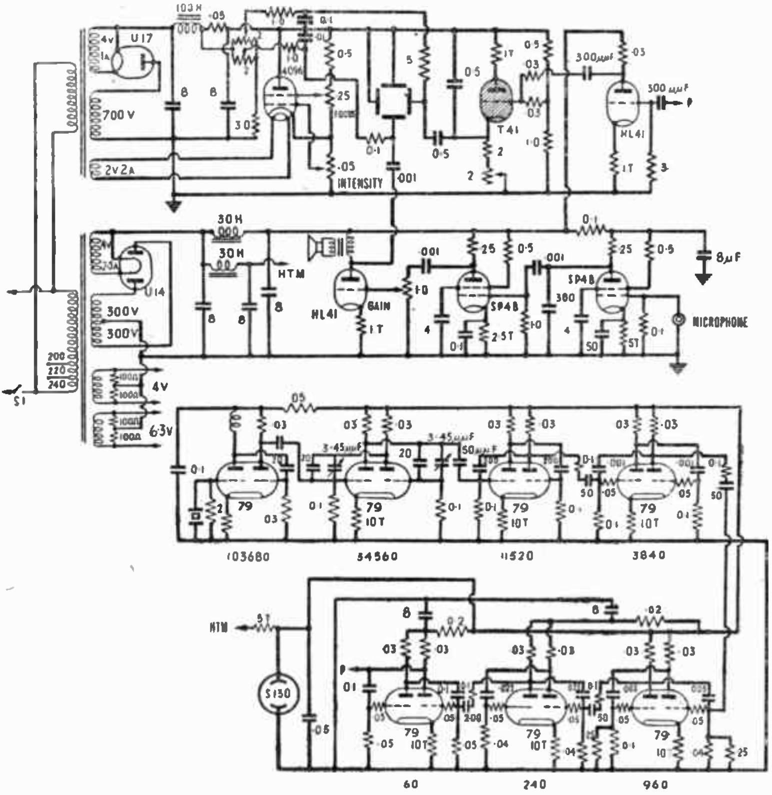


Fig. 7.

In the case of the paper record the successive marks on the paper are no all adjacent, but lie on one side or the other of the mean position, which again drifts to one side or the other unless the watch is exactly right.

Electrical Micrometers

The use of electrical methods of measuring small changes of distance is well known. Sometimes the distance measurement is incidental to some other factor. For example, it is possible to measure the strain in material by fixing to suitable parts of the mechanism a device which changes its electrical properties if subjected to tension or compression. An ordinary carbon resistor is such a device, and in the early days much information was obtained by fixing rods or strips of carbon composition to suitable parts of a structure and noting the change in resistance.

Such changes are usually periodic—e.g., the flexing of the tip of a propeller blade will go through a cycle of changes which recur once every complete revolution. Therefore the changes in resistance can be converted into voltages which are suitably amplified and applied to a cathode ray tube, the time base of which is synchronised with the rotation of the propeller.

Carbon rods in compression were used in the early experiments on indicator diagrams in which the explosion pressure in an internal combustion engine was recorded against the stroke of the piston, again using a cathode ray tube in which the X sweep was either generated by or made proportional to the stroke of the piston and the Y deflection was proportional to the pressure developed. Carbon, however, has the disadvantage of a large temperature coefficient so that the zero is liable to wander, and it has other disadvantages which render it an unstable agent. Quartz has been used to convert the pressures developed into electrical voltages, and more recently capacity changes have come to the fore and are now very popular.

The manner in which the capacity change is detected varies. One method is to use a tuned circuit which is maintained in a state of oscillation, and to arrange that the capacity of the pick-up is connected across the tuned circuit, and thus controls its frequency within a small range. By passing this voltage to a frequency discriminating circuit the change in frequency can be converted into change in amplitude, and this can be caused to operate a cathode ray tube or other indicator. For many purposes the side of the resonance curve is quite satisfactory as a discriminator, though some of the special types of circuit used for automatic frequency control or the reception of frequency modulated waves can be used if desired.

Vibrations in Journals

Another application of some interest was the investigation of the vibrations in the bearings of a turbo-alternator rotor.

The rotor must be dynamically balanced, and while any out of balance will result in vibration in the journals it is not easy to ascertain the exact points on the rotor at which mass must be added or removed to effect a balance. It is, in fact, necessary to know the phase of the out of balance forces as well as their magnitude.

In the case in question this information was obtained electronically by using a seismograph coupled to a cathode ray tube. Mounted on the journals was a large mass suspended upon a thin comparatively flexible support, the mass and elasticity being so calculated that at the frequencies in question the mass would remain stationary while the journal itself vibrated.

The position of the mass relative to the rest of the equipment was then determined by a small electrical pick-up, which, in this instance, was electromagnetic. The arrangement is illustrated in Fig. 8. The change in inductance produced by the movement of the armature closer to the pick-up coil throws the bridge out of balance and therefore develops a voltage which is passed to the amplifier and subsequently applied to a cathode ray tube. The time base of the tube was mechanically driven from the rotor of the machine so that as the rotor was run up to speed the sweep of the spot on the cathode ray tube was always equivalent to one revolution of the rotor. The vibrations produced by the out of balance forces are periodic, consisting of a fundamental at the frequency of the rotor speed, together with possible harmonic components. Thus the synchronising of the time base in this manner resulted in a stationary waveform on the cathode ray screen, from the phase (and amplitude) of which the desired information could be obtained.

By arranging one pick-up on each of the journals it was possible to compare the out of balance forces at each end of the rotor, and by using an electronic switch or a double beam tube the two images can be superposed. An additional advantage of this particular method was that the balancing pick-up in the bridge network was made identical with the actual pick-up, and the position of its armature was controlled by a micrometer head. It was then possible to calibrate the apparatus in terms of actual movement of the seismograph head, a change of one micron being quite easily detected.

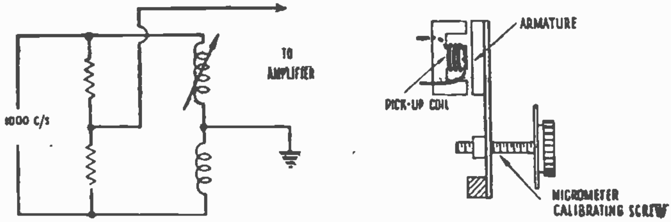


Fig. 8.

Magnetising

An application of electrical methods to rather larger powers is that of the magnetising or demagnetising of magnets employed in many industrial instruments such as revolution counters, tachometers and similar devices. These to-day are very often of magnetic construction in which a small permanent magnet is rotated by a shaft and operates the indicating mechanism by eddy current drag. The usual practice is to make the magnet stronger than required and to adjust the amount of magnetism when the instrument is assembled until the indication is correct.

It is comparatively easy to demagnetise the magnet by passing short bursts of alternating current through a coil placed around the instrument, but this has two disadvantages. In the first place, the A.C. produces eddy current heating in the instrument itself which may invalidate the reading. Secondly the heat developed in the coil is very considerable. The use of a larger coil does not get over the difficulty, because this prevents the flux from being concentrated in the place where it is required, and the only remedy is to change the coil at frequent intervals.

It will be appreciated that in the interests of permanence of calibration the magnetic circuit of the instrument is made nearly closed. Hence, if it is desired to alter the magnetism when the instrument is completely assembled a very powerful demagnetising force is required, and it is desirable to concentrate this as far as possible. An electronic method of achieving this is shown in Fig. 9. A double commutator was arranged to select one cycle in every twenty from the ordinary 50 cycle supply. The circuit was completed through a mercury vapour rectifier, which actually acted as a switch. Thus the commutator merely made the circuit in a suitable condition to conduct, but the rectifier began to conduct at the beginning of the positive half cycle, and cut off the current at the end. Thus the commutator had no switching duty to perform and the rectifier selected exactly one half cycle every 0·4 seconds.

This technique reduced the heating in the coil some forty times straight away, which, in turn, permitted the coil to be wound in a much smaller compass. This increased its effectiveness for the particular operation, with the final result that not only was the arrangement more powerful than before, but it was possible to keep it in continuous operation because the coil did not over-heat. Moreover, it was possible by reversing the direction of the coil to re-magnetise the system should it have inadvertently become demagnetised too far. This, again, was a great time saver, and the production in one particular instance was increased 300 per cent. by the use of this modified form of equipment.

Conclusion

These few examples by no means exhaust the possibilities. They are chosen at random to show the way in which electronics can be used for the assistance of industry. Some of the devices described were production applications enabling the ordinary manufacturing processes to be speeded up, while others were pure research and enabled results to be obtained which could not be produced by any other means. Indeed, it is not too much to say that, in the hands of the experts, the electronic device can be made a tool of the highest precision, and if the designer will take the necessary care to ensure reliability, industry is waiting to avail itself of the new technique.

DISCUSSION

The Chairman (Mr. G. A. V. Sowter):

" Mr. Reyner's Paper has covered, in an interesting way, many applications of electronics to industrial problems, and will undoubtedly stimulate thought and discussion.

" With regard to measuring thickness within fine limits, there is available an instrument for the continuous testing of metal strip as it passes through rolling mills. The device consists of two hardened wheels between which the strip travels and an armature is attached to one of the wheels which can move in guides. The movement of the armature alters the mutual inductance of two coils forming part of a 50 c.p.s. bridge, and for a particular thickness setting, the bridge is arranged to be balanced. When the thickness varies, the armature position is changed and the out-of-balance current is indicated on a robust form of workshop galvanometer. This enables the operator to control thickness within a fraction of a thousandth of an inch and make adjustments to the rolling plant whilst strip is in the process of being rolled. This is a very important electronic application.

" I was interested in Mr. Reyner's reference to an oscillator where close adjustments can be made on a dial, because already some manufacturers are putting on to the market resistance capacity oscillators which can be set by adjusting precision resistances. Excellent performance is claimed.

" In connection with the voltmeter mentioned by Mr. Reyner, he may also know of the multi-range wattmeter which has an accuracy within something like 0·5 per cent. when using negative feed-back.[8]

" Finally, I concur that engineers do appreciate the use of instruments which incorporate valves, and on this premise I open the meeting for discussion, with a very warm welcome to members of other Institutions who are present to contribute their experiences."

Mr. W. S. Earle (Associate Member):

" I should like to know the period of time over which the negative feed-back oscillator was constant to 13 parts in a million per degree Centigrade. Further, I should be glad if Mr. Reyner would say what resistances were used in the feed-back oscillator."

Mr. Reyner :

" Over a period of a day we plotted the various points of frequency against temperature, and they all lay quite close to a line drawn through the middle of them. Any erratic variations were of a very small order, certainly less than 10 per cent. of what we were looking for. Owing to the fact that the instrument was required immediately for use, we had not time to make a long-period stability test.

" The resistances used were the ordinary wound wire resistances."

Mr. M. Levy (Associate Member) :

" I was very interested to hear Mr. Reyner, and especially noted his emphasis that negative feedback, in improving the stability of electronic circuits and in making the characteristics practically independent of valve changes, has made possible the use of electronic circuits in industry, where the greatest requirement is reliability.

" I pointed out these qualities of negative feedback in some patents and publications which appeared in 1932-33.[1] However, some eminent technicians to whom I presented this theory told me that ' it was not of interest to improve the stability of a circuit if at the same time one reduced its sensitivity.' Shortly afterwards, in April, 1934, S. H. Black published his famous paper.

" I should like to make some comments on Mr. Reyner's paper. First, concerning the resistance capacity oscillators, I took out a patent on these circuits in 1932, but it was not followed by a publication, and this early work apparently is not known.

" Secondly, Mr. Reyner has pointed out that the output of an oscillator can be made to vary less with frequency by adding a diode conveniently biased in parallel with the tuned oscillating circuit. He may be interested to know the results of some experiments. I have used this method on a high-frequency oscillator and have observed that the improvement is not very great. Graphically the results can be represented by curves 1 and 2 of Fig. 9.

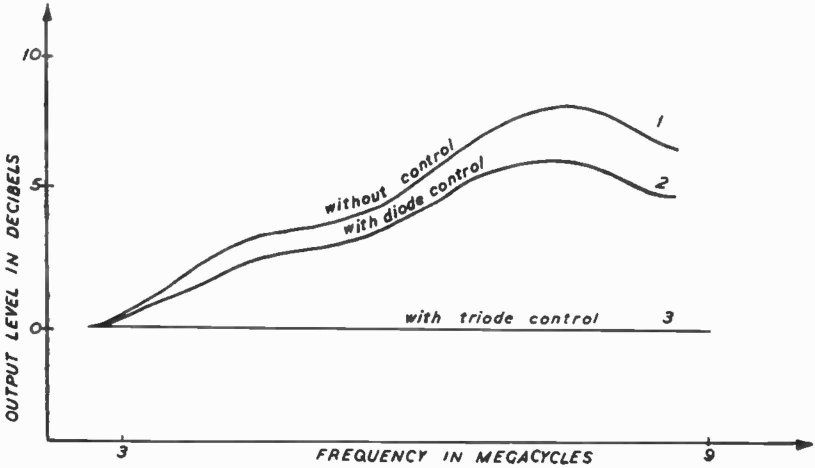


Fig. 9.

"Without control, the output varies 200 per cent. when the frequency is changed over the whole range (curve 1); with diode control the variation is reduced by about 20 per cent. (curve 2). Then I tried to improve the method by replacing the diode by a triode, according to the circuit in Fig. 10, and I obtained a constant output all over the range (curve 3).

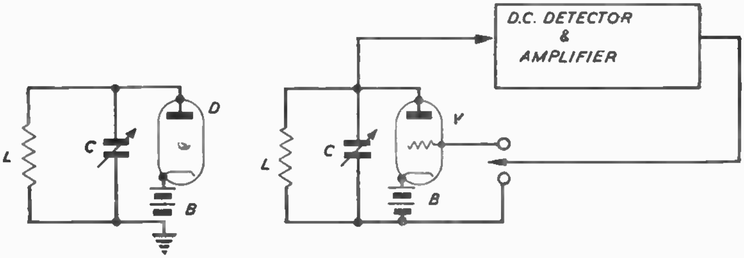


Fig. 10.

"This result can be explained very simply. The oscillating voltage across the tuned circuit is detected, amplified and transmitted to the grid of the triode. The cathode-plate part of the triode has the same control effect as a diode. However, if μ_1 is the amplification factor of the triode, any variation of voltage applied on the grid has the same effect as a variation μ_1 times greater than when applied on the plate. If the amplification factor of the detector amplifier is μ_2, any variation of the oscillating voltage in this circuit has the same effect as a variation $\mu_1 \mu_2$ times greater in a diode control circuit. μ_1 is usually greater than 10 and μ_2 can easily be of the order of 100 with a single valve; the triode circuit has a stabilising effect at least 1,000 times greater than the diode circuit.

"The experimental circuit is schematically represented in Fig. 11. This circuit has been the subject of experiment with a multi-range oscillator covering the 50 Kc.-10 Mc. band, and the output was made absolutely constant in each range.

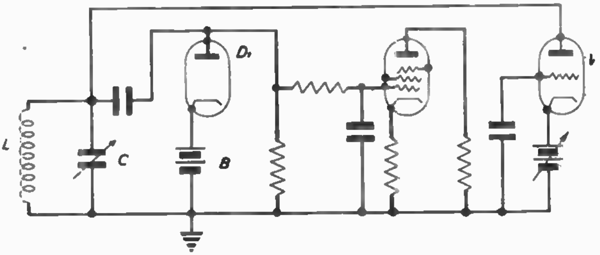


Fig. 11.

"Other methods, sometimes more simple, can be used,[6] but they do not give such perfect results.

"Thirdly, I note that Mr. Reyner obtains a great sub-division of frequency in using a great number of multivibrators in series, each one introducing a frequency division of 2. Each multivibrator being synchronised on the second sub-multiple of the control signal, no jumping from this sub-multiple to another should occur if the circuit is well adjusted. However, this method requires a number of multivibrators which increase with the order of the sub-division required. For a sub-division of 16 the method requires 4 multivibrator circuits.

"It is actually possible to obtain great sub-division orders with one multivibrator only combined with a feedback circuit.

" A circuit has been suggested by Builder.[7] He can obtain sub-division of the order of 10 without any possibility of jumping to another sub-multiple. It is my impression that sub-divisions of the order of 20 to 30 can easily be obtained with the same stability. I am experimenting on this and hope to give the results at a later date."

Mr. W. A. Beattie (Member) :

" I was very interested in Mr. Reyner's remarks concerning the measurement of small movements. In 1922 Professor Dowling devised his ultra-micrometer, in which he used the simplest possible electronic circuit. It consisted merely of an oscillating triode circuit in which the valve was adjusted to half-way between the no-oscillation and the fully-oscillating condition. I have seen valves remain in that condition for a period of weeks. When the condenser across the grid circuit was varied by very small amounts, equivalent to fractions such as a millionth of an inch, there was quite a considerable indication of variation. Indeed, in the original demonstration, given by Professor Dowling, of the ultra-micrometer, he put a live bean between the plates of the condenser and showed how one could actually see the growth of the bean in jumps by means of a spot light arrangement. It is rather interesting that that very simple micrometer used by Professor Dowling made use of a valve ; I have used carbon resistances for measurement, and it seems that we have completed a circle and have now come back to the use of valves as used originally in 1922 for this purpose.

" Recalling Mr. Levy's illustration of a constant r.f. output circuit, I remember that a somewhat similar arrangement was used by Baird Television for lining up the i.f. circuits visually with the aid of the cathode ray oscilloscope. For some time they experimented with the conventional condenser sweep arrangement and found that the output from that was all over the place. Then one of their engineers devised the constant output circuit, and he definitely used a meter to ensure constant output. That proved to be an extremely useful application where one had to achieve calibration over a very wide range."

Mr. Hopkins :

" I should be glad if Mr. Reyner would amplify his remarks on the pick-up used for measuring the vibration of a ' singing ' steam pipe or water pipe."

Mr. Reyner :

" It was an ordinary vibration pick-up of the Rochelle salt type, which is commercially available on the market ; there was nothing special about it. It is manufactured by the Brush Electrical Company, and it was used very effectively. It is made up into quite a small unit, and you just apply it wherever you like, depending, of course, upon the approximate location of the vibration. It is in effect a gramophone pick-up adapted to the detection of small vibrations."

Mr. J. C. T. Gilbert (Member) :

" I should like to add to the list of electronic devices by calling attention to an equipment known as a ' resonoscope ' which was introduced from

America. The idea behind it was to enable any unskilled person to tune a piano, and it consisted of a series of tuning forks, each a semi-tone apart and mounted on a turret-head; the turret-head rotated, and the tuning forks caused to vibrate or oscillate in an oscillator circuit, the output of the oscillator circuit being fed to the ' x ' plates of an oscillograph. A moving-coil pickup was placed on the piano, the output fed to an amplifier, and the output of the amplifier fed to the ' y ' plates of the oscillograph. The turret head was set to any note and the tension of the string adjusted until a stationary sine wave was seen on the tube. A snag was the temperature instability of the tuning forks."

A Visitor:

" Recalling Mr. Gilbert's remarks concerning the application of electronics to the tuning of musical instruments, undoubtedly there is considerable difficulty in securing the necessary frequency stability when groups of tuning forks are used. I would suggest the possibility of using some form of electromagnetic generator, using 12 shafts, the speed of each shaft being increased progressively. The sub-division of frequency would enable a very high degree of accuracy to be attained, and it could then be applied selectively on a cathode ray tube to synchronise the string when it is being tuned. By that means also the apparatus could be considerably cheapened.

" I was particularly interested in Mr. Reyner's reference to the oscillator which uses the resistance capacity method. Bearing in mind the frequency stability suggested, I should like to know just what is the variation of frequency with time."

Mr. Reyner:

" We have not detected any frequency instability; it is something considerably less than the temperature coefficient. We have not made a study of the long-period instability, but it will be of the order of a few points in a million. You can change valves and can almost put in valves of a different type; so long as you are working within the characteristic of the valve, the stability does not alter."

Mr. Sherman:

" With regard to crystal vibration pick-ups, as a rule there is definitely a difference between a gramophone pick-up unit and a vibration pick-up. In the gramophone pick-up the vibrations are transmitted through the needle point. In the vibration pick-up the crystal is suspended in one of two ways. In the first case the free end of the crystal can vibrate simply due to inertia; in the other case both ends are clamped, and the centre is allowed to vibrate. The only difference between those two arrangements is that the self-resonance frequency is roughly double in one case as compared with the other.

" There is another basic difference between the types of vibration pick-ups, in that you can use either a crystal which will act as a bender or, alternatively, one which will act torsionally. That, of course, depends on the particular application. Crystals can be provided for use at frequences up to 20,000 or 30,000 cycles, and there are others nearer to the 500-1,000 cycle range. Also, the sizes of the crystals vary considerable. A crystal used in a stethoscope, with a flat resonance curve, may be as big as 1½-in. square and ⅛-in. thick, whereas the bender type is very much thinner and may be only ¾-in. square. Very thin crystals, of only a few thousandths of an inch thickness, are particularly sensitive to noises such as the ticking of a watch, and can be used also as microphones."

Mr. Cotton :

" In view of Mr. Reyner's reference to electronic watch-timing devices, I would point out that the application of electronic apparatus to the timing of watches is somewhat limited, due to the fact that the majority of watches are not isochronal ; i.e. their rate depends to a very large extent upon how how far they are wound up. Further, the average user does not want to know the instantaneous rate of a watch, but rather the rate over a period of time ; and there the timing devices have a great limitation. I am told that these devices are very useful for finding faults, but that the loud-speaker amplifier is probably more useful to watchmakers than is the cathode ray tube ; the average watchmaker can interpret sound more easily than he can interpret a picture, and therefore he can learn more by sound than from a picture.

Mr. Spear :

" Although Mr. Reyner has not mentioned the use of the cathode ray tube for measuring the speed of the shutter of a camera, can he give an indication of the degree of accuracy within which that can be achieved ? "

Mr. Reyner :

" The accuracy is almost anything that you like to make it. After all, you can measure micro-seconds in a cathode ray tube, which is probably faster than anything you are concerned with in a camera shutter. It is a matter of having a single sweep device in the photographic record, and a little ingenuity is needed in finding a way of doing it. You can start the spot sweeping across the screen just before you make or break the shutter, and you can make the shutter itself operate a device which produces a record on the screen. You can make it interrupt a beam of light, or something of that sort ; and you can certainly get your answer to a micro-second."

Mr. S. A. Hurren, M.C. (Fellow) :

" I have the privilege to propose the thanks of the meeting to Mr. Reyner for his most interesting paper. He has given us a great deal of information to think about, and there is no reason why we should not all put our heads together in connection with the development of the application of electronics to industry."

The vote of thanks was carried with enthusiasm, and Mr. Reyner briefly responded, and the meeting adjourned at 9.5 p.m.

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[7] G. Builder.—*A Stabilised Frequency Divider.* Proc. Amer. I.R.E., April, 1941, pp. 177-181.

[8] K. A. MacFadyen & N. D. Hill.—*G.E.C. Journal.* Vol. XI. No. 3. February, 1941.

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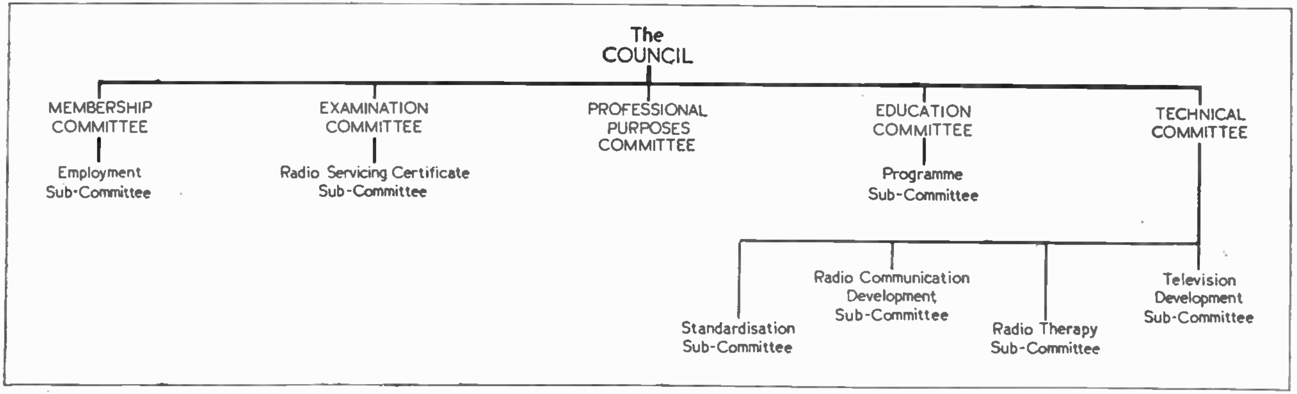

During the year ended March 31st, 1943, the Education and Examination Committees combined and the Programme and Editorial Committee was appointed as a Standing Committee.

BOOK REVIEWS

High Frequency Thermionic Tubes. By A. F. Harvey, B.Sc.(Eng.), D.Phil.

When great strides are being made in ultra high-frequency engineering practice, and very little information may be published for reasons of security, this work is a valuable contribution to the science. Although a great deal of information concerning V.H.F. valve technique has been published in short articles, no collated source of information has previously been available.

The first chapter covers in logical sequence the whole field of normal thermionic valves within limits at which the effects of frequency are negligible. Chapter 2 describes the effects on performance of higher frequencies, and modifications in valve design to overcome them. Chapter 3 describes special types of oscillators, especially suitable for generating very high frequencies, which operate by virtue of electron inertia, and describes their mechanism.

The next two chapters, comprising over 50 pages, deal exclusively with the magnetron, giving data resulting from research by the author and many other workers. The last chapter is concerned with special modulation and amplification considerations, using the Rhumbatron and the Klystron, and finally, wave guides and horn radiators as wave propagators.

Price 18*s*. net. Library No. 514.

Radio Receiver Design, Part One. By K. R. Sturley, Ph.D., B.Sc., A.M.I.E.E.

The author endeavours in this work to cover as fully as possible the whole field of radio receiver theory, commencing at the aerial and following through in practical sequence to the final output and power supplies. Owing to war conditions, the whole book has had to be divided into two volumes, of which this is the first. This may not be to its detriment, since Part One includes over 400 pages. The treatment is founded on a sound technical basis, and constitutes a complete designer's text book ; this volume taking the user up to detector stage.

A brief introduction is followed by considerations of amplitude, frequency and phase modulation, and a chapter of about 40 pages deals with valve theory. Wave propagation, aerials of various types and the associated coupling circuits ; radio frequency amplification and selectivity ; frequency changing problems and oscillator circuits for superheterodynes ; intermediate frequency amplifiers ; and detectors follow in that sequence, and finally, two sections explain the use of " j " notation and the Fourier series.

The explanations are clear, and the book is well illustrated with diagrams.

Price 28*s*. net. Library No. 334.

The Technique of Radio Design. By E. E. Zepler, Ph.D.

This book commences with a statement of fundamental facts, mainly concerning inductance, capacity and tuned circuits, and then proceeds in succeeding chapters to deal with such problems as RF couplings, detection, frequency changing, selectivity, gain control, screening, feedback, hum and so on, explaining the design features of the relative circuits and pointing out possible weaknesses and methods of overcoming them. Twelve pages are given to a chapter on " Receiver Noise," eighteen to " Gain Control," twenty-three to an excellent explanation of " The Principles of Screening," and thirty-five to " Undesired Feedback." There is a short chapter on distortion, and a few pages on power supply, which could with advantage have been increased in scope.

Calculations and formulæ are given throughout, but complicated mathematics have been excluded as far as possible. The book is copiously illustrated with diagrams, and these and the tables are well placed. The main subject matter is preceded by a list of symbols used in the book and inductive formulæ. Price 21s. net. Library No. 326.

All the above books have been received from the publishers, Chapman and Hall, Ltd., 11, Henrietta Street, London, W.C.2. [Reviewed by E. A. W. S.]

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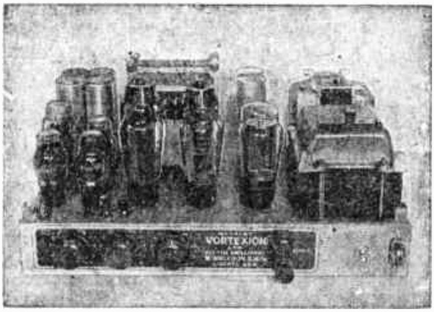

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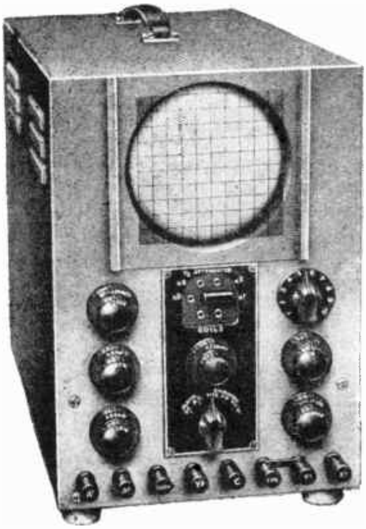

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SEPTEMBER-OCTOBER, 1943.

" To promote the general advancement of and to facilitate the exchange of information and ideas on Radio science."

THE ANNUAL GENERAL MEETING OF THE INSTITUTION

The Eighteenth Annual General Meeting of the Institution (the Tenth since Incorporation) was held at the Institution of Structural Engineers, in London, on Friday, the 3rd of September, 1943, commencing at 6.20 p.m.

Sir Louis Sterling (President) was in the Chair and was supported by Mr. Leslie McMichael and Dr. James Robinson (Vice-Presidents), Mr. L. Grinstead (Chairman of the Council), other members of Council and G. D. Clifford (Secretary).

After the Meeting had approved the minutes of the Annual General Meeting held on the 29th May, 1942, Sir Louis Sterling proposed the adoption of the Annual Report and Accounts and Balance Sheet as follows :—

" All members have received the current issue of the *Journal* (June-August) which contains the Report and Accounts. In its relation to last year's Report, it should be noted that attention to training and educational facilities has again been prominent in the work of the Council and its Committees.

" The need for that deliberation has also been emphasised in the continued work of the Membership Committee, notwithstanding the considerable increase in the Institution's membership.

Proposed Research Organisation

" Through the Parliamentary Committee, the views of all Committees are being obtained on a proposal to be discussed during the next twelve months concerning the formation of a British Radio Research Organisation.

" The function of the proposed Research Association or Institute is to be the pursuit of basic research of the type that has hitherto suffered restriction owing to its high cost, the absence of obvious practical applications or the poor prospect of early financial returns.

" It is suggested that progress reports describing the results of the work of the Institute should be published at regular intervals and that no restriction be placed upon access to these reports or upon the private, commercial or industrial employment of the information contained therein.

" Such an Institute should be directed by an impartial Board, comprising, we suggest, nominees from industry, from the Government and from the British Institution of Radio Engineers.

" We are hoping—and the Government has shown a very big interest in the matter of combined research—that in the course of time a Government grant can be obtained, provided of course, that industry subscribes an equal amount, to prosecute research in the interests of industry and science.

The Institution's Committees

" Members of the Institution are indebted to the Committees for their work during the past year. In war-time, meetings are not easy to arrange, and much of the work undertaken has had to be done in the private time of members, which is already fully taxed.

The Accounts

" Financially, as well as in the other directions mentioned, the Institution has developed. We are particularly indebted to manufacturers[1] who have so generously contributed to the funds of the Institution and have enabled us to clear the deficit which accumulated in the early years of the Institution's history.

Retiring Members of Council

" It is fitting that we should make reference to the work of the retiring Members of Council. In an Institution such as ours it is always advisable periodically to receive new ideas and new trends of thought ; that is achieved by the retirement of half the Members of Council each year. But it should not be thought that the retiring Members have in any way exhausted their usefulness to the Institution. By their efforts, the Institution has continued to make good progress, and we hope that they will be able to continue their good work through the various Standing Committees. We are very grateful to them for the work they have done.

" I have very much pleasure in recommending the adoption of the Annual Report and the Accounts and Balance Sheet, as published in the current issue of the *Journal.*"

The motion for the adoption of the Report and Accounts was seconded by Captain G. W. Grant (Associate Member) and was carried unanimously.

Election of President and Vice-Presidents

Mr. L. GRINSTEAD: " I have the privilege of proposing the election of our President and Vice-Presidents for the ensuing year. Sir Louis Sterling was first elected President of this Institution last year, and we hope to retain his services in that capacity in the ensuing year. It is worthy of mention that, during the past fifteen months, he has attended not only every meeting of the General Council, but also various meetings of the Standing Committees. My colleagues on Council and Committees will testify to his invaluable help in framing the policy of the Institution and in developing our work.

" A most ardent supporter of the Institution in many ways for the past five years, Sir Louis has given unstintedly of his time and does not restrict his advice and help solely to Council and Committee meetings. Always accessible, he has been nominated by the retiring Council to continue in office for a second year. I feel sure that, in your usual manner, you will wish to show your approval of his acceptance of that nomination.

" The names of the Vice-Presidents whom I am sure we shall be honoured to elect are:—

Admiral the Lord Louis Mountbatten.

Sir William Noble.
Dr. James Robinson.
Mr. Leslie McMichael.
Air Vice-Marshal R. S. Aitken.

" I have pleasure in proposing the election of the gentlemen I have named."

The motion was seconded by Mr. J. L. Thompson (Member) and carried unanimously.

The PRESIDENT: " I thank you all very much on behalf of myself and my colleagues. Speaking for myself, I deem it a very great honour to be elected President for a second year. One's election for the first time, of course, might almost be an accident; members may be justified in taking a chance! But if, after having served for a year, a man is re-elected to his office, then he may be excused if he feels that he may have done a good job. I assure you that in the coming year I shall continue to do the best I can in the interests of the Institution, which it is an honour to serve."

Election of General Council.

The PRESIDENT: " The names of members nominated for election to the General Council for the year 1943/44 are published on page 177 of the August issue of the *Journal*. No further nominations having been received, I have pleasure in proposing the election of the gentlemen named."

The resolution was carried with acclamation.

The PRESIDENT: " I have very great pleasure in welcoming our newly-elected Vice-President, Air Vice-Marshal Aitken, and our new Members of Council, Mr. Bedford, Squadron-Leader Chapman, Mr. Dimmick, Dr. McLachlan and Lt. Col. Northey. We can be satisfied that we have elected gentlemen whose services will be of the very greatest help to this Institution in future years."

Election of Solicitors and Auditors

Messrs. Braund & Hill, of 6, Gray's Inn Square, London, W.C.1, and Messrs. Gladstone, Titley & Co., of 61-63, St. Paul's Churchyard, London, E.C.4. were re-elected Solicitors and Auditors respectively, to the Institution.

Awards to Examination Prize-Winners

Presidents Prize and Mountbatten Medal

The PRESIDENT: " It is my privilege and pleasure to present to Mr. LEONARD W. BLICK two awards to mark his success in the Institution's Graduateship Examinations. The occasion is unique in the history of the Institution, in that both awards have been made to one candidate. The President's Prize is awarded to Mr. Blick for having gained first place in the years' examinations, and he receives also the Mountbatten Medal as the most outstanding of the candidates in the three Services. I congratulate him on his unique achievement."

The L.R.C. Prize

The PRESIDENT announced the award of the L.R.C. Prize to Mr. JOHN POLLARD, who gained second place in the past year's examinations. Mr. Pollard was unable to attend the meeting to receive his prize.

The business of the Annual General Meeting closed at 7.5 p.m.

Address by Sir Ernest Fisk

Following the Annual General Meeting, Sir Ernest Fisk, Immediate Past-President of the Australian Institution of Radio Engineers, delivered an address in which he surveyed radio development in Australia. His paper will be reported in full in the December issue of the *Journal* (Vol. 3, No. 7).

(¹) The British Tungsram Radio Works Ltd., should be added to the list of manufacturers given in the June/August, 1943 Journal.

The

British Institution of Radio Engineers

MODERN MAGNETIC MATERIALS

(With special reference to permanent magnets and high permeability alloys).

A discussion by the London Section
on March 19*th*, 1943, *opened by :—*

G. A. V. Sowter, B.Sc., M.I.E.E. (Member)
A. J. Tyrrell, A.M.I.E.E. (Associate Member)*

The discussion opened with the following paper on "soft" magnetic materials or high permeability alloys by G. A. V. Sowter :—

I will confine my remarks to high permeability alloys in so far as they have application or are related to permanent magnetic materials, and it will be seen that there is a surprising similarity of technique in the production of these two types of alloys.

Obviously, there are hundreds of magnetic alloys which may be called "soft," and it is not desired to catalogue all their properties. First, reference should be made to the B-H curves of three materials covering the range of magnetic induction with which we are concerned. Fig. 1 is a logarithmic arrangement, with the "B" axis vertical and the "H" axis horizontal.

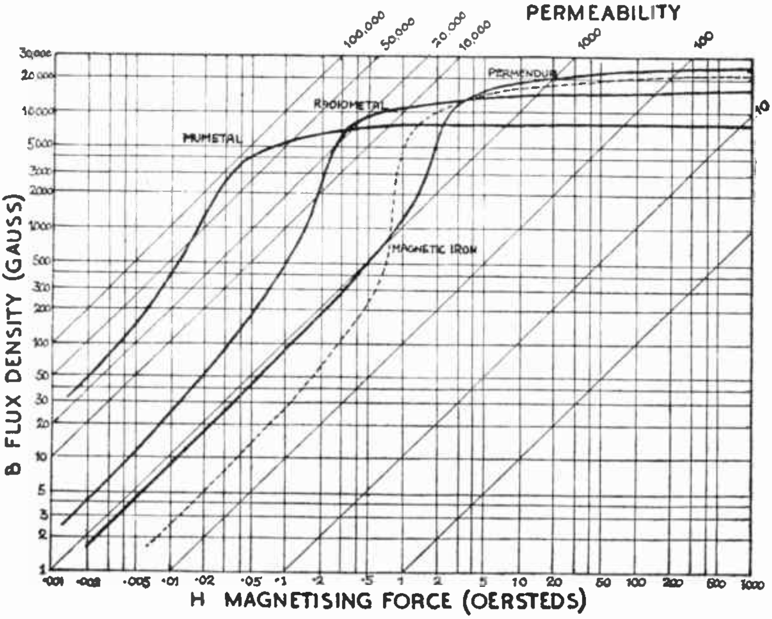

Fig. 1.

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* Mullard Wireless Service Co. Ltd.

The curve for Mumetal indicates the small values of " H " required to create appreciable values of " B " and also the fact that it tends to reach its saturation before any other material. The value of $B_{sat.}$ is about 8,000 gauss, whilst Radiometal has a saturation of about 16,000 gauss. Permendur has the highest saturation of any known material, reaching the figure of 26,000 gauss.

I do not think it is very well known that if one has a B-H curve of this nature one can draw diagonal lines which will indicate the permeabilities. Thus there is a line on the graph representing a permeability of 100,000, and others for 10,000, 1,000 and so on. The maximum permeability of Mumetal is about 90,000, Radiometal about 20,000, and Permendur in the region of 7,000. I recommend this method of drawing B-H curves and permeability curves on the same sheet ; it has much in its favour. Fig. 2 represents data from various sources,[1,2] and is an effort to tabulate the normal " soft " magnetic materials, the alloys being classified in order of their saturation flux density.

Permendur heads the list, and although used to a small but increasing extent in this country, has wide application in the United States. It consists of 49% Cobalt, 49% Iron plus 2% Vanadium, which is added to render it ductile and capable of being rolled so that it can be used as diaphragms and in the form of flat sheets.

Cobalt-Iron (35/65) is another alloy noted for high saturation, but offers machining difficulties and is expensive. Electrolytic Iron, Dynamo Steel, Swedish Iron and Armco Iron are all materials which are used where heavy fluxes are carried, and, unlike the preceding alloys, are relatively cheap. The list now continues in descending order of saturation, but contains alloys which have high permeabilities at low values of " H." In this respect, Hipernik and Mumetal are noteworthy, whilst Perminvar is remarkable for its extremely small hysterises loss. Both Cobalt and Nickel have appreciable magnetic properties even when unalloyed with any other elements.

When in any device permanent magnet materials are associated with " soft " magnetic alloys, the latter will carry unidirectional or polarising flux and must operate under incremental conditions.

Fig. 3 gives curves[3] of incremental permeability (μ_Δ) plotted against B_p, the polarising flux density, and is enlightening in certain respects. The three curves of Fig. 3 roughly form an envelope, inside which falls all other known magnetic alloys. For values of B_p up to 7,000 gauss, Mumetal has the highest incremental permeability, a fact which is not generally appreciated. Radiometal has superior properties over the range of B_p 7,000-11,500 gauss, whilst above this figure Permendur V is outstanding.

The general application of the latter is only limited by its cost, and frequently for economic reasons materials which are less suitable magnetically are employed. It is worth mentioning that in many devices operating under incremental conditions (e.g. permanent magnet telephone diaphragm) the output is proportionate to $2B\text{-}\delta B$ where B is the permanent magnet induction and δB is the small change of flux due to a small change of " H." It follows that the highest operating values of B as well as μ_Δ are generally desirable.

Development of Soft Magnetic Materials

During the past 20 years, enormous advances have been made in the production of high permeability alloys and in particular those consisting mainly of two or three of the elements Nickel, Iron and Cobalt. Considerable research has been carried out, and it has been proved that magnetic performance is strongly influenced by the following factors :—

Values of Flux Density B (Gauss)

H → Oersted	.02	.05	.1	.4	.5	.8	1	1.2	2	5	10	20	50	100	200	500	1,000
Permendur	—	43	—	—	—	—	1,300	—	10,500	19.100	23,400	26,000	—	—	—	—	—
Cobalt Iron 35/65	—	—	—	—	—	—	—	—	—	15,000	18,000	—	21,000	23.300	—	25,200	26,000
Electrolytic Iron	—	—	—	—	7,500	—	10,200	—	—	16,200	—	—	17,100	18.000	19,500	21,700	22,500
Dynamo steel .08C	—	—	—	—	—	—	4,000	10,000	13,500	—	15.800	16,500	17,500	19,000	21,000	—	—
Swedish Iron	—	—	—	—	2,000	—	7,000	—	10,500	13,000	—	15.200	—	17,300	—	—	—
Armco Iron	—	—	—	—	400	—	4,700	—	12,000	—	14,600	—	15,900	16,800	—	—	20,000
2½% Silicon Iron	—	—	—	—	—	—	5,880	—	10,500	—	14,000	—	17,100	17.800	—	—	—
4% Silicon Iron	—	—	—	—	4,500	—	9,000	—	10,000	—	—	—	15,300	17,900	—	—	—
Hypernik	180	1,800	5,500	10,300	—	—	11.300	—	—	—	—	—	—	—	—	—	—
Radiometal	50	200	500	—	9,000	—	11,000	—	12,500	—	15,000	—	16.000	—	—	—	—
Perminvar 45Ni 30Fe 25 Co	—	—	2,100	—	—	—	8,600	—	—	—	11,000	—	—	—	—	—	—
Permalloy 78/22	500	1,850	4,200	9,500	—	—	—	—	—	—	—	—	—	—	—	—	—
Mumetal	1,400	4,000	5,500	—	—	—	7,500	—	—	—	—	—	—	—	—	—	—
Cobalt	—	—	—	—	—	—	—	—	—	500	—	—	—	9,500	—	11,500	13,500
Nickel	—	—	—	200	—	400	—	600	—	3,500	—	—	—	5,440	—	6,500	7,000

Fig. 2—Flux density and magnetising force of various soft magnetic materials.

(*a*) Composition.
(*b*) Heat treatment for relief of mechanical strains.
(*c*) Heat treatment in special gases such as hydrogen.
(*d*) Controlled cold working by rolling or drawing.
(*e*) Influence of magnetic field during cooling portion of heat treatment cycle.

(*a*) *Composition.*—It has been shown elsewhere that with the nickel iron family of high permeability alloys the initial and maximum permeability and saturation vary distinctly with the nickel content, and in fact there are certain compositions which are even non-magnetic. The influence of small quantities of other elements[4] such as for example Chromium, Molybdenum and Copper is noteworthy in improving desired magnetic properties and the optimum composition is usually a compromise based on the desirability of reasonable mechanical or handling properties in addition to magnetic performance. The purity of ingredients is of prime importance and has led to high frequency furnace melting. In some instances melting *in vacuo* has been adopted to eliminate oxides and even absorbed gases.

(*b*) *Heat treatment for relief of mechanical strains.*—This has always been a standard practice for high permeability alloys, particularly after machining or operations involving cold working. Commercial hot rolled silicon iron alloys are generally stamped and used without further heat treatment, although it is known that an improvement of about 10% in permeability and loss figures can be achieved by suitable annealing. The reason why heat treatment is not generally carried out is purely a question of cost, since furnace operations of the nature required are fairly expensive. With nickel iron alloys heat treatment is absolutely essential since with Mumetal, for example, the maximum permeability may only be about 100 in the cold rolled condition and yet exceed 100,000 after annealing.

(*c*) *Heat treatment in special gases such as hydrogen.*—This method of heat treatment in hydrogen eliminates oxides and other impurities in the material, and in the past there has been a suggestion that with nickel iron a combination of hydrogen and nickel iron was produced. Views have since changed, and hydrogen is now regarded solely as a cleansing agent. An outstanding example of this effect has been described by Cioffi,[5] where by soaking for 18 hours at 1,480 degrees C., followed by 18 hours at 880 degrees C., both in hydrogen, he raised the initial permeability of Armco iron to 20,000 and the maximum permeability by 340,000. In addition, the hysteresis loss was considerably reduced.

With nickel iron alloys also, heat treatment in hydrogen can have markedly beneficial effects on permeability and loss, particularly if the soaking is prolonged. The American alloy, Hipernik, is subjected to this treatment in production and exceptional properties are claimed. From the speaker's own experience, it can be substantiated that Radiometal is beneficially influenced by a hydrogen soak at high temperature, and appreciable reduction in hysteresis has resulted by this process.

(*d*) *Controlled cold working by rolling or drawing.*—This is probably the most important discovery in production technique during the last decade, and much of the work carried on in this country is due to W. F. Randall, the well-known metallurgist. It is found that the influence of cold working exceeds that of any other process and that not only is permeability improved several-fold, but losses are also considerably reduced. Some alloys are more susceptible to this treatment than others, but in every case is the effect beneficial. What actually happens to the crystal structure is a fitting subject for discussion, but it is known that the cold working during rolling tends to orient the crystals so that generally their axes are in alignment with the direction of rolling. The effect on the physical properties is to render the material anistropic, and the highest permeability and lowest losses occur along the rolling direction. The striking advantage of clock spring or spiral cores over rings punched from the same material, as mentioned in a previous paper[6], is an index of this property. Obviously, then, the best magnetic cores for transformers will consist of those whose flux follows the rolling direction and standard laminations will not take maximum advantage of the improved properties. It should perhaps be mentioned in this connection that with specially cold worked materials there is always an overall improvement in properties, irrespective of how stampings, for example, are punched with respect to the rolling direction. In some cases strips are preferred to laminations (particularly under present delivery conditions), but obviously additional manual labour in assembly is involved. Probably the astounding permeabilities along the axes of a single crystal of hydrogen-purified iron spread most light on this subject and reference is made to the work of Cioffi and Boothby[7]. The latter made measurements on a single crystal cut to form a hollow parallelogram, and obtained values of maximum permeability greater than 1,250,000 along certain axis directions.

(*e*) *Influence of magnetic field during cooling portion of heat treatment cycle.*—In so far as high permeability alloys are concerned, the first published data on this treatment was in 1935, and describes work carried out by Dilinger and Bozorth[8]. A straightforward 65/35 nickel iron alloy was subjected to 18 hours heat treatment at 1,400 degrees C. in hydrogen, heated to 650 degrees C. in 1 hour and cooled in a magnetic field of 16 oersteds in hydrogen. The maximum permeability in this case was raised to 610,000, which represents a considerable advance over the 20,000 usually obtained for commercial material of this nature.

Speaking from experience, it can be stated that during the cooling period of the heat treatment of Mumetal, it has been found that the application of a magnetic field considerably improves the magnetic properties of the alloy, and permeabilities of the order of 200,000 have been obtained. The process has never been carried out on a large scale although many specimens have been produced, and it has been suggested that the effect occurs at the Curie point temperature (about 480 degrees C.). It is thought that the magnetic field tends to offset the slight strains set up at this change point, due to the very small magnetostriction of the alloy, but the conditions for successful operation are fairly critical, and offer a useful field for research. It is recorded by Ruder[9] that 6% Silicon Iron, a fairly brittle but nevertheless useful transformer material, has also very low magnetostriction and responds remarkably well to the influence of a magnetic field during the heat treatment cycle.

In view of its pronounced effects, it is not surprising that the process is also used for permanent magnet alloys, and Mr. Tyrrell will give some information on this aspect.

Trend of Development

About 20 years ago, the best magnetic materials available were either fairly pure irons, or various grades of silicon iron, the best of which had an initial permeability of about 300 and a maximum permeability approaching 6,000 only. Since then, the alloys with nickel as an important constituent, have been produced on a large commercial scale, and it is reasonable to state that magnetic properties have improved about ten-fold.

Generally the improvements have covered every aspect, although the most pronounced effects have been associated with permeability and losses.

With regard to permeability, it is obvious from the laboratory results mentioned that further advances in commercial production are possible, and from the theoretical point of view there is no limit to the values of μ_0 and $\mu_{\text{max.}}$ which may be obtained.

The losses consist of hysteresis, eddy-current and "nachwirkung" effect loss and are not mutually dependent. Pure hysteresis as measured by ballistic methods can be reduced to extremely small values, as in the case of Mumetal, whilst the Perminvar type of alloys cited in Fig. 3 can be manufactured to have negligible hysteresis at low densities. Unfortunately, some of these alloys are susceptible to the influence of uni-directional magnetising force, and acquire a loss loop when magnetised. So far, this has precluded the use of Perminvar for certain loaded cables. The eddy current component of loss depends purely upon the electrical resistivity of the magnetic alloys under consideration, so that certain constituents are added definitely to increase this property. Thus, Chromium or Molybdenum increases resistivity of the 80/20 type of nickel iron very considerably, but the extent of the addition is limited by the effect of the Cr or Mo upon saturation and permeability. Whilst resistivities in excess of 100 microhms/cm^3 are possible, the overall effect on magnetic properties is bad when this figure is achieved.

The limit of saturation induction appears to have been reached at 26,000 gauss with Permendur, and there is no reason to presume that this will be exceeded. There did exist a limiting value of about 22,500 gauss many years ago, which was termed "ferric induction saturation," but obviously this has been surpassed.

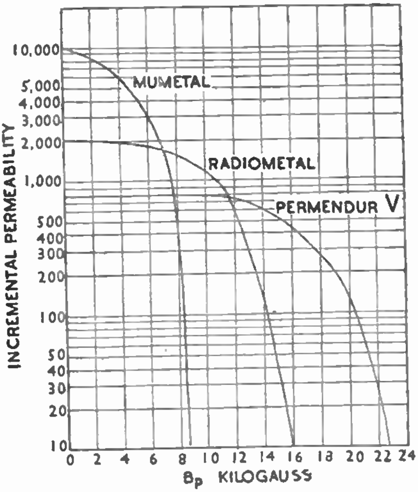

Fig. 3.

Finally, the question of economics must enter into the utilisation of enhanced properties, since in many cases the cost of the improved alloys prohibits their general adoption. Nevertheless, by scientific design it is frequently possible to reduce the cost of devices by the careful selection of that particular alloy which is applicable to the conditions of operations.

In these opening remarks I have not mentioned practical applications which were considered on a previous occasion[6] but there is no reason why any particular points should not be raised in the subsequent discussion. My object in this preliminary dissertation has been briefly to supply the facts and figures and to trust that they will provide suitable material on which you may contribute your views.

PERMANENT MAGNET ALLOYS

Mr. A. J. Tyrrell :

The earliest permanent magnets on record were the pieces of lodestone which were found to adhere to iron under favourable conditions, and when suspended, to set themselves in a certain direction with reference to the earth's magnetic field. From that time to the present day, magnet materials have been the object of much interest and research. Iron alloyed with relatively small amounts of other elements has been found to give a whole series of alloys with improved magnetic properties, so that to-day there are available permanent magnet alloys with energy outputs considered impossible a few years ago.

In this connection, it is noted that in his classical paper read before the I.E.E. in 1912, Professor S. P. Thompson stated, "The ideal sought for at the present time, is a steel of such composition that when properly treated it shall have a remanence of 800, and a coercive force of 80. No such steel has yet been produced." T. F. Wall in 1926 quoted the above and said, 'To-day, steels are available, and are used, having a remanent intensity of magnetisation (B_r) of over 900, and a coercive force (H_c) of over 200." The art has now advanced so rapidly since 1926 that commercial materials are now sold having B_r values of 12,000, and H_c of 600-700. A complete family of curves (Fig. 4) illustrates this last statement.

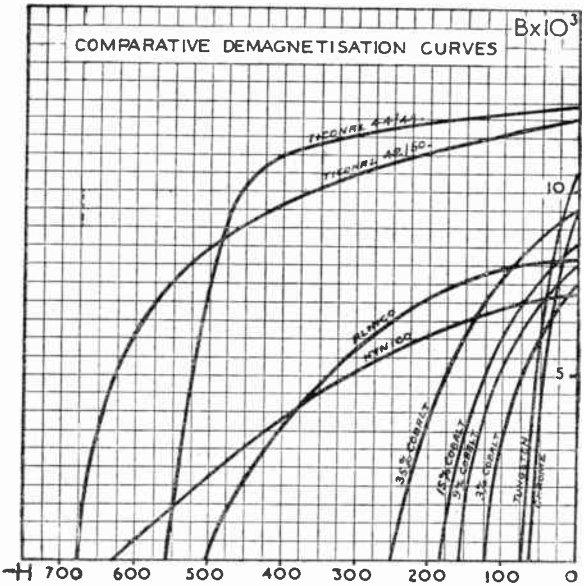

Fig. 4.

Comparative demagnetisation curves of commercially obtainable permanent magnet alloys.

In order to appreciate these curves some explanation is probably necessary.

Criterion of a Good Permanent Magnet Material

The criterion of the performance of a permanent magnet material is best illustrated by its hysteresis loop (Figs. 5 and 6). The so-termed "Demagnetisation curve" is that portion contained within either the second or fourth quadrants.

The point where the curve cuts the B axis gives the maximum flux per sq. cm. remaining in a closed magnetic circuit of the material after temporary saturation, and is known as remanence, or residual induction (B_r). The point where the curve cuts the H axis shows the reverse M.M.F. which must be applied per cm of length to reduce B to zero, and is known as the coercive force (H_c).

Both of these conditions are of little practical value since, in the first case, the magnet material is short circuited, and in the second is supplying no flux. Any point along the B.H. curve indicates a condition where magnetic energy is available for use in an external magnetic circuit.

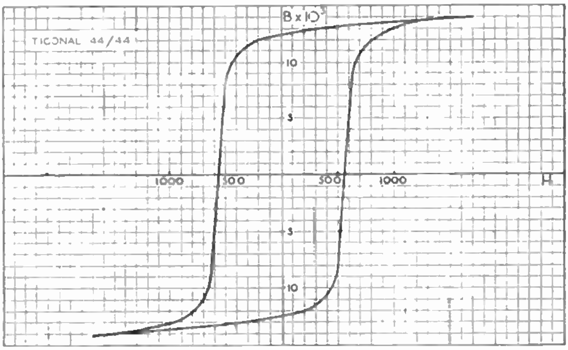

Fig. 5.
Hysteresis loop of Ticonal 44/44.

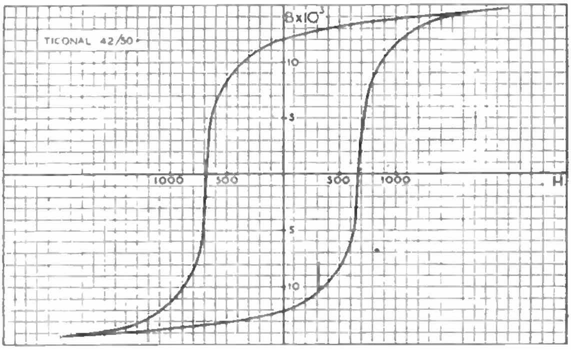

Fig. 6.
Hysteresis loop of Ticonal 42/50.

The energy available is proportional to B × H, and is usually plotted as B.H. against B (see Figs. 7 and 8). The maximum value of B.H. is the theoretical limit of energy available per unit cube of alloy in an external circuit, and is the criterion or "figure of merit" for a permanent magnet material.

An approximate method of deducing these operating values is to complete the rectangle enclosing the B.H. curve and to draw the diagonal (Fig. 9).

The intersection of this line and the B.H. curve is the approximate operating point. This condition is obtained in practice either by adjusting the physical dimensions of the permanent magnet or modifying the external reluctance.

It is interesting to note that if a line is drawn as in Fig. 9, the following relationship holds :—

$$\frac{H}{B} = \text{Tan}\,\alpha = \frac{\text{Reluctance of external circuit.}}{\text{Reluctance of space occupied by magnet.}}$$

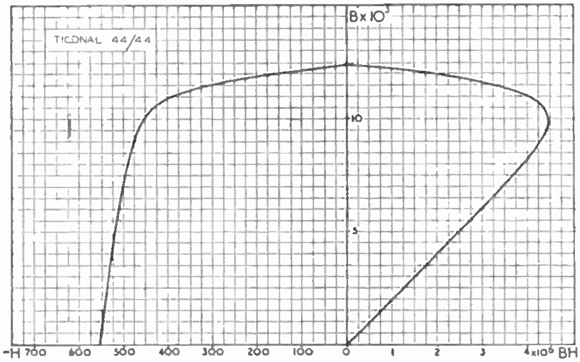

Fig. 7.
Demagnetisation and energy product curve of Ticonal 44/44.

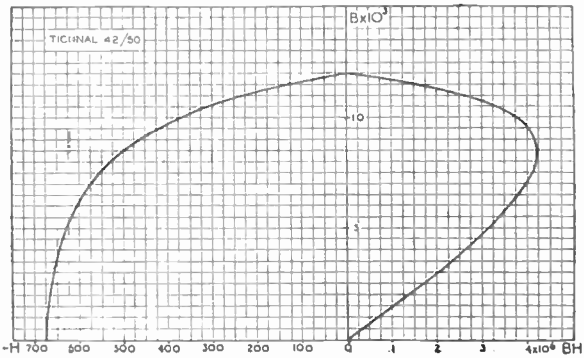

Fig. 8.
Demagnetisation and energy product curve of Ticonal 42/50.

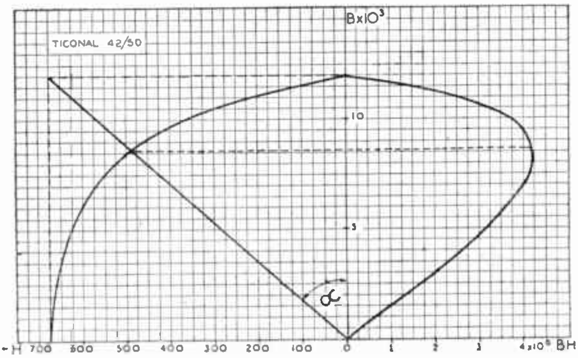

Fig. 9.
Graphical method of deducing the approximate optimum operating point on the demagnetisation curve of a permanent magnet alloy.

This is of value in computing operating flux densities when the leakage factor is known.

If the demagnetisation, and B.H. against B. curves of the commercially obtainable alloys are shown on the same scale (Fig. 10), their merits may thus be compared at a glance.

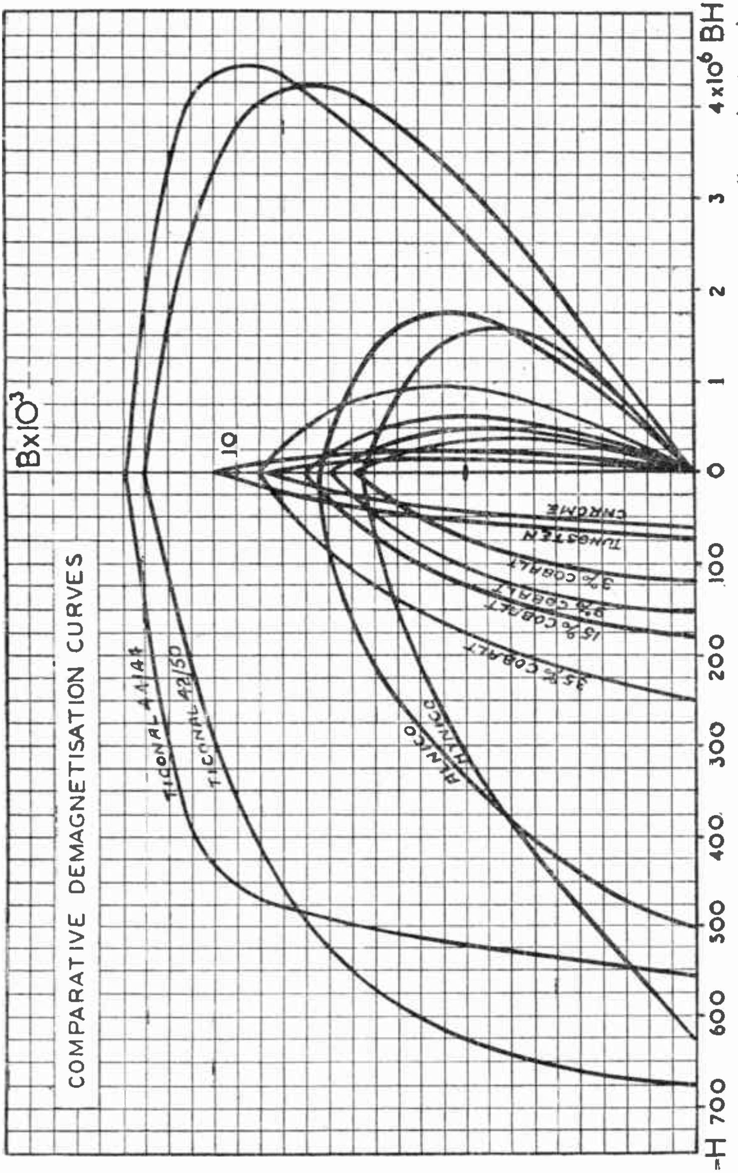

Fig. 10.—Comparative demagnetisation curves of commercially obtainable permanent magnet alloys showing the energy product curves plotted as B.H. against B.

The following table (Fig. 11) should be of particular value to designers.

Material	B_r	H_c	B (working)	H (working)	$(BH)_{max.} \times 10^6$
Ticonal 44/44	12,200	555	10,000	445	4.45
Ticonal 42/50	12,000	675	8,440	500	4.22
Alnico	8,200	507	5,620	310	1.74
Hynico	7,250	628	4,660	350	1.63
Alni	6,300	506	4,240	300	1.27
Hynical	5,250	674	3,290	350	1.15
35% Cobalt	9,500	250	6,000	160	0.96
15% Cobalt	8,500	180	5,200	125	0.65
9% Cobalt	8,000	155	5,000	110	0.55
6% Cobalt	7,900	135	4,700	90	0.42
3% Cobalt	7,500	120	4,400	84	0.38
Tungsten steel	10,500	70	7,000	47	0.33
Chrome steel	9,500	60	6,200	45	0.28

(This table is based on the average properties to be expected from these materials and shows B and H at optimum operating points.)

Commercial Production of Permanent Magnet Alloys

The general melting technique follows closely that used for high permeability nickel-iron magnetic alloys, and subsequent heat treatment is also an essential operation. Some years ago it was discovered that the magnetic properties of some alloys could be improved if they were heat-treated in a strong magnetic field. The process was not commercially used as the improvement scarcely merited the additional difficulties and costs of processing.

After considerable work in the Philips laboratories, a range of alloys was developed where the improvement in magnetic properties due to special heat treatment in a magnetic field is truly remarkable (British Patent No. 552,731). These alloys, containing aluminium, copper, nickel, titanium, cobalt and iron, may have a $(B.H.)_{max}$ of 5×10^6 or more under favourable conditions, and in production a value of 4.0 to 4.5×10^6. Magnets manufactured from this material are marketed as " Ticonal " (Regd. Trade Mark) in this country and Alnico V. in U.S.A.

One particular feature of alloys heat-treated in a magnetic field lies in their anistropic characteristics. A pronounced magnetic axis exists, and the optimum properties of the material obtain when the operating flux is parallel to this axis. A marked falling off in properties occurs when flux deviates from this direction, as is indicated in curve Figs. 12 and 13.

Figs. 12 *and* 13. *The normal demagnetisation and energy curves A of Ticonal* 44/44 *and Ticonal* 42/50. *The marked fall in magnetic properties curves B when the operating flux is at* 90° *to the magnetic axis.*

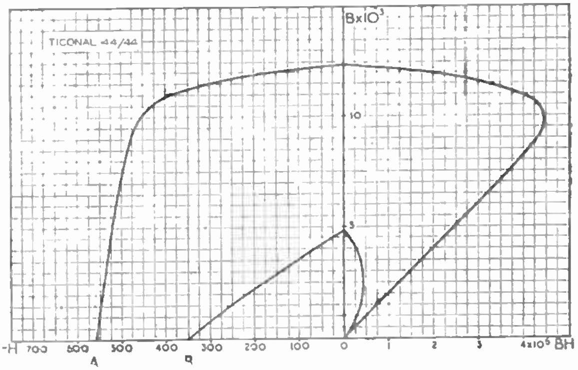

Fig. 12.

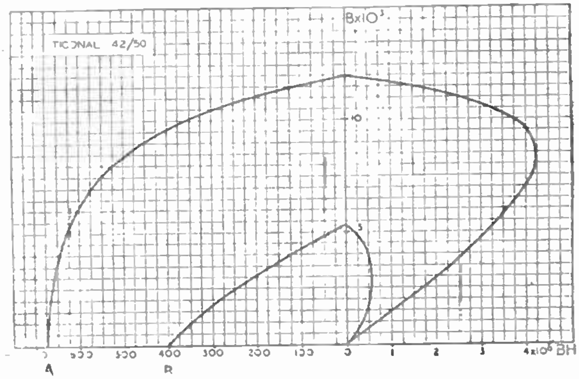

Fig. 13.

Design

Permanent magnet materials of this type with their remarkable energy products $(B.H.)_{max}$ have far-reaching effects on design. The mass of permanent magnet material is not only reduced in inverse proportion to the increase in $(B.H.)_{max}$, but the apparatus as a whole may usually be re-designed into a smaller, more compact and magnetically more efficient construction, thereby effecting a further reduction in the mass of permanent magnet material required.

The new alloy has applications where in the past only energised magnets could be used. It also enables one to make certain constructions in which energised magnets cause serious difficulties with respect to winding space and heat dissipation.

Magnetising Permanent Magnets

In order that a permanent magnet shall work efficiently it must be fully magnetised, preferably by saturation *in situ* in its working magnetic circuit. This can usually be done by putting the magnet material between the poles of a powerful electro-magnet and applying sufficient magnetising force to reach the desired value of flux density.

In some cases saturation cannot be effected in this way and a heavy current generator or an impulse transformer may offer a solution.

The exceptional energy output of this new permanent magnet alloy may be better appreciated when it is realised that a "Ticonal" magnet, 1 in. long, will give with correct design, the same magnetomotive force as a winding of 1,000 ampere turns.

DISCUSSION

Mr. D. A. Griffiths (Associate Member) :

Mr. Tyrrell has mentioned the differences in the magnetic properties of a material according to whether it is worked in one direction or another and whether one measures across or along the working axis. What has Mr. Sowter to say on that matter in regard to the soft magnetic materials? I ask the question because, about a month ago, I obtained some inconsistent results, which I can attribute only to that factor.

Mr. Sowter :

The nickel iron alloys, and Mumetal in particular, are cold-worked so that the optimum properties lie along the direction of rolling. If one compares, for example, some stamped rings and a spiral core made up from a strip of material in which the optimum properties lie along the grain, surprising results are obtained. The use of spiral cores instead of rings was first suggested in order to avoid or reduce waste, for the making of rings results in a good deal of scrap, but it has been found that the spiral core is better than the rings, because it utilises to advantage the aeolotropic nature of the material. Recently a representative of a Government Department stated that one of the Staff had examined the properties of Mumetal spiral cores and compared them with rings, and found that, not only are the spiral cores better than rings with regard to losses and permeability, but also in respect of remanence. In order to utilise Mumetal to the best advantage one should ensure that it is in such a form that the flux distribution is along the rolling direction.

Curves showing results obtained with spiral cores and rings made from the strip indicate that strip cores have permeabilities of the order of 20 per cent. to 60 per cent. better than rings according to the value of H at which the comparison is made.

Mr. F. E. Lane (Associate Member) :

I notice a tendency, in more recent meter practice, to use laminated permanent magnets. I should like to know the reason for that.

A Visitor :

A reason given to me on one occasion for the use of the laminated magnet was that of standardisation. Makers of specialised types of meters sometimes have to build up larger magnets ; and if they wish to make a cheaper one, they leave out one lamination.

Mr. Sowter :

I think the meter manufacturers generally use quite low grade permanent magnet materials. It is sometimes claimed that the performance of a laminated magnet is superior to that of a solid type, but I think this can only be due to the fact that more uniform heat treatment is possible with laminæ, particularly if quenching is part of the hardening process. In A.C. domestic Watt-hour meters silicon-iron laminations are invariably used for the magnetic system and in some cases in order to improve the performance at very light loads a single Mumetal lamination is included. This means that loads of even less than 5 watts will be recorded so that the old idea of obtaining a small load of 5 watts continuously without payment is no longer possible.

Mr. Phillips (Borough Polytechnic):

I was associated with magnets and magnet steels during the last war. I have had very little to do with this particular subject since then, but I cannot help feeling that the manufacturers are extremely fortunate nowadays in two respects. In the first place, at a certain period during the last war somebody unearthed the idea of coercive force and remanence. Until then those terms were practically text book terms, except to a few people. At about that time I had to concern myself with magneto magnets, and coercive force and remanence were specified. The second matter in respect of which the manufacturers to-day are fortunate relates to mechanical tests. After magnets were tested for suitable magnetic properties, they were tested mechanically by dropping them from a height of 6 ft. on to a concrete floor. In those earlier days, of course, magnets were large. The average coercive force specified then for aeroplane engine magnets was 58 oersted and the remanence 10,000 gauss. The maximum value of H, which was usually imposed on those magnets, was 400 or 600. Whilst one firm would produce hard magnets giving a coercive force of 70 or 80 and remanence at somewhat about the figure I have mentioned, many of its magnets would not stand up to the mechanical test. But another firm, producing a rather softer magnet, which was rather poorer magnetically, would find that its products would pass all the tests. I fully realise that if there is a large coercive force and a large remanence, the magnet can be smaller, but I should like to know whether any work has been done on the mechanical properties from the point of view I have mentioned.

About the year 1916 our aeroplanes were failing mainly on account of the fact that the magnets were not standing up to their work, either magnetically or mechanically. A difficulty we had to contend with was that the trade—and here again I am speaking with knowledge—was not at all clear as to what constituted a good magnet. The problem was how to measure the coercive force and how to test the magnets in bulk. At that time there was only one reliable method of testing a magnet, and the test occupied about three hours. It was part of my job to try to test 500 or so in half an hour. One had to satisfy oneself that a magnet was satisfactory, and also to satisfy the manufacturers.

It is wonderful that so much progress has been made in this country since those days, and that the manufacturers have risen to the job so well as they have.

I am also interested in the non-magnetic steels, which were first used at about the time of which I am speaking for parts of magnetos.

Mr. Tyrrell:

It is quite true that the tungsten and chromium steels are better magnets when tempered to be glass-hard and then they are weak mechanically. As would be expected, a good magnet made of such material will probably break as a result of being dropped. This tendency still persists with other alloys, and, generally, the better the material magnetically the more brittle is its nature. Some of the materials are so brittle that they may even shatter during heat treatment, and if a magnet of this type is broken and examined the structure will be found to resemble that of an early wireless type crystal. The faces of these metallic crystals are sometimes as much as 1/8 in. across.

Dr. N. G. R. Partridge (Member):

I am intrigued by the process of hydrogen soaking. As I understand it, the material is soaked in hydrogen at a high temperature for a relatively short time with somewhat astonishing results. Of necessity the material is subsequently soaked in the atmosphere at normal temperatures for the remainder of its existence. Will the results of the hydrogen soaking slowly pass away?

I should also like some information about the effect of stress upon Mumetal. In particular, when assembling a transformer core it is convenient to align the laminations by the simple process of hitting them with a hammer. But subsequent test results are liable to be disappointing! To what extent can one use physical force upon this material?"

Mr. Sowter:

Hydrogen treatment can be considered as essentially a cleansing process. If the material contains oxides and oxygen, the oxides may be reduced to the original metallic elements by the chemical effect of the hydrogen. Since there must be very great molecular mobility at the high temperatures employed (900 deg. C. to 1,100 deg. C.), I think it most unlikely that ordinary temperatures will affect the treated materials. The oxides are formed during the melting process and I think one can say that the effect of the hydrogen cleansing treatment is permanent. It is assumed now, I think, that even a much less obvious effect, the influence of magnetic fields during annealing is permanent, although there remains much more to be said about this.

With regard to strain, it is always suggested in connection with Mumetal that if it is not deformed beyond the elastic limit no harm is done. If, for example, Mumetal wire is loaded by weights so that it is in tension, the original properties are regained on removing the stress provided always that no permanent set has been acquired. It is generally accepted that, if one must hit Mumetal laminations, it is best to use a copper or soft hammer, but it is not advisable to hit them. A lot of liberties can be taken with Mumetal, provided it is treated as something which should not be deformed. If it is handled as though it were a material such as glass, or porcelain, it will retain its properties indefinitely and will withstand considerable handling.

Experiments made many years ago on Permalloy wire under tension[8] showed that, as the stress was increased, so the permeability improved and the hysteresis became less and less. In the same way it was found possible to have Mumetal, under similar conditions of strain, with very little or no hysteresis. It is perhaps not very practical to utilise stretched Mumetal wires as a magnetic core so that this exceptionally low hysteresis condition should be regarded rather as an academic curiosity. In support of my statement, however, that Mumetal will retain its properties indefinitely if it is not deformed beyond the elastic limit, there is the fact that the standard instrument transformers at the National Physical Laboratory have Mumetal cores. One can presume that, if these changed their properties with time, they would not be used for this purpose.

Mr. Lane:

I should like to know whether an electric furnace is used for the hydrogen soaking process. Further, does it employ hydrogen from cylinders, or in the form as produced from ammonia?

Mr. Sowter:

Invariably one uses a muffle furnace for heating, so that it does not matter much whether it is electric or not, but generally speaking, electric furnaces are utilised.

For small furnaces, expensive hydrogen from cylinders is convenient but for larger ones cracked ammonia is found to be satisfactory.

Mr. Lane:

It occurs to me that if one uses an electric furnace with a spiral element one may get a magnetic field from it which affects the process, particularly if the frame of the furnace is not a magnetic shield.

Mr. Sowter:

It is possible, but improbable, and much as I should like to think that the spirals of furnaces do create a magnetic field, I should say that it is most unlikely that the strength is adequate to influence the resulting properties of the material being annealed.

A Visitor:

I wonder what happens to these special materials when they are subjected to additional heat-treatment such as, for instance, in welding processes. Thus in connection with C.R.O. Screens I have seen brackets attached after they have been annealed. Will the process of attaching those brackets ruin the properties of the materials ?

Mr. Sowter:

When welding Mumetal it is necessary to use Mumetal for the welding rod, and this must not be oxidised during the process. Since finished articles, are subjected to a heat-treatment temperature, near 1,100 deg. C., it is impossible to use copper rivets or pieces of brass, as attachments, since they will flow during the heat-treatment. The heat-treatment relieves all mechanical strain, but if one cools or quenches rapidly, or cools too slowly, there is a tendency to affect the properties of the material in an adverse manner. If one has an annealed cathode ray tube screen, for example, and wishes to attach brackets, it can be spot-welded successfully, but one should localise the region over which the heating is applied. Where the material is made red hot there will be a tendency to reduce the permeability, but with a cathode ray tube screen I should doubt very much whether one could detect visually the difference between attaching the brackets before or after heat-treatment. For optimum performance it is correct to heat-treat after attaching the brackets.

Dr. Partridge:

I should like some information as to the suitability, or rather, the difference of efficiency of the nickel irons for screening against D.C. fields, permanent magnet fields and alternating fields. Is there a very marked difference ?

Mr. Sowter:

Mumetal is used very much for screening transformers, cathode-ray tubes, and the like against mains pick-up. It can also be used to eliminate the earth's field and is employed in this manner for certain types of astatic galvanometer. There is a basic difference between, say, screening a permanent magnet and an energised transformer. With a permanent magnet, generally speaking, the flux is limited and there is a definite maximum amount of flux one may obtain from it. Provided the screen is placed at such a distance from the magnet that the Mumetal does not saturate by reason of that flux, the screening can be made adequate. With a transformer, or where there are ampere turns (D.C. or A.C.) available, it is obvious that if the Mumetal offers a reasonable proportion of the reluctance of the external circuit, there will be more flux created, due to the presence of the Mumetal. The effect of gaps is thus of even greater importance under such conditions.

The National Physical Laboratory[10] has tested 1/16-inch Mumetal at various frequencies. At 50 cycles, when enclosing an input transformer there was 36 dB reduction in pick-up, and when enclosing an exciting transformer the figure was 30 dB. As the frequency was increased to 1,600 cycles, the relative values dropped to 32 and 29 dB. At 3,200 the figures were 26 and 22 dB respectively, and at 6,400 cycles 20 and 8 dB respectively. Even at 6,400 cycles, therefore, there was fairly good screening. If one wants a really efficient screen, operating over a wide audio frequency range, the correct design procedure is to provide a copper screen inside the Mumetal box.

As a matter of interest, 1/32-inch copper, tested under the same conditions at 50 cycles, gave a screening effect of only 4 dB, as against 36 dB for Mumetal. At 6,400 cycles, the figure for the copper was 13 dB, against 20 dB for Mumetal. Thus, at the frequency of 6,400 cycles, 1/16-inch Mumetal was still better than the 1/32-inch copper. Some 1/16-inch steel gave a figure round about 6-8 dB throughout the frequency range from 50 to 6,400 cycles.

Mr. E. A. Benwell (Visitor) :

What is the screening effect of Mumetal at supersonic frequencies ?

Mr. Sowter :

It is not possible to go into that in great detail, but owing to the eddy current shielding effect, the penetration is very much reduced with frequency. Mumetal, due to its high resistivity, will definitely screen over the audio range, and if the alloy is made sufficiently thin it has some effective permeability even at a frequency of several megacycles. Laminations of 0.015-inch material will show an appreciable reduction of permeability from 50 to 1,000 cycles, due to skin effect, and at 5,000 cycles the value may be only 500-800. In 0.005-inch material, the reduction of permeability with frequency is very much less marked.

A Visitor :

Mr. Tyrrell has shown how Ticonal should operate on an ideal point on the BH curve. How is this done ? Secondly, what is its stability compared with that of other alloys ?

Mr. Tyrrell :

A magnet should be so designed that the back magneto motive force caused by the flux in the air gap or load divided by the length of the magnet gives a value corresponding to the optimum working H (or magneto motive force per unit length of magnet material used). After complete saturation the magnet automatically settles down to a point on a demagnetising curve corresponding to this value of H providing the cross section is correctly designed.

A practical example would illustrate the point more clearly. Consider a magnetic circuit which requires a total flux (including leakage flux) of

25,000 lines and requires a magneto motive force of 1,500 oersted to maintain this flux. This condition is to be maintained by a permanent magnet of Ticonal 42/50 which gives optimum energy when working at approximately H=500 and B=8,000.

$$\text{The length of magnet required}=\frac{\text{Magneto motive force required}}{\text{Working H of alloy}}$$

$$=\frac{1{,}500}{500}=3\text{ cm.}$$

$$\text{Cross section of magnet required}=\frac{\text{Total flux required}}{\text{Working flux per sq. cm. of alloy}}$$

$$=\frac{25{,}000}{8{,}000}=\text{approx. 3.1 sq. cm.}$$

With regard to stability of Ticonal, after the magnet has been saturated and the magnetising force removed, the operating point swings back along the BH curve (demagnetising curve) to a point corresponding to the H being used. During the first hour the flux will fall by about 3% and thereafter the rate of fall is extremely slow. If the material is subjected to a further demagnetising influence in order to bring the flux down by another 3% or 4%, the stability is such that after this the change is difficult to measure. Information from America indicates that the extent of the change is approximately 0.1% during the first year and thereafter even less.

Mr. H. Tyrrell-Gramann (Associate) :

With regard to magnets for loud speakers, can the acoustical output of a loud speaker be increased greatly by the use of hard magnets or soft magnets suitably energised ?

Mr. Sowter :

It is known that, apart from optimum moving coil dimensions, the acoustical output is a function of B_g^2, where B_g is the flux density in the useful part of the gap. Therefore, if one can increase the B in the gap the efficiency of the loudspeaker can be improved. The earliest energised type of magnets were made of cast iron, and many ampere turns were needed to get a value of B_g of about 6,000 gauss. The best magnet that was made at about the period 1928-30, was of dynamo steel having very low carbon content and with that was achieved about 10,000 B_g and a total useful gap flux of the order of 200,000 gauss. In 1932-33, Dr. N. W. McLachlan wrote an article in the "Wireless Engineer," describing an energised type of magnet made from Armco iron which was heat-treated and with that magnet a value of B_g of about 15,000 gauss resulted.

The limiting factor on energised magnets is not the number of ampere turns that one can accommodate but the material of the pole pieces, i.e. that portion of the magnetic circuit through which the flux into the gap has to pass. Since I have mentioned that the best materials known saturate at 26,000 gauss it is obvious that due to leakage one will not achieve the full value of 26,000 B_g. In the past, with very good magnets, the useful flux one could get in the gap was only about 40% to 50% of the flux which was carried by the central core. It follows that, unless one has a particularly fine design or very small gaps, it is doubtful whether one could ever obtain more than 20,000 B_g. The same will apply to permanent magnet materials, but the new alloys must offer a distinct advance. For expensive loudspeakers one can reckon that permanent magnet materials will be used invariably, the loudspeaker manufacturers possibly taking advantage of the properties of cobalt iron or Permandur to carry the flux in order to reduce the leakage in the neighbourhood of the gap. If the makers of domestic radio sets can construct cheaper loudspeakers by using permanent magnet material they will do so, but we should like to hear Mr. Tyrrell's views about commercial loudspeakers for this market.

Mr. A. J. Tyrrell :

With regard to using permanent magnets for loudspeakers, here is a permanent magnet unit for an average domestic loudspeaker. It contains a slightly tapering short cylinder of Ticonal of less than a cubic inch in volume. The reason for its small size is that while the efficiency of the material causes a reduction in dimensions of the magnets in inverse proportion to the increase in magnetic efficiency of the alloy, the iron circuit is made so small and compact that leakage areas are reduced to the barest minimum. This results in a further decrease in the amount of magnet alloy required. This unit (demonstrated) has a flux density of 9,500 in the gap.

If a speaker is required with rather more than average sensitivity this type of magnet cannot always be employed, in which case the standard construction with a ring of magnet material has to be used with its somewhat higher leakage factor.

Permanent magnet speaker assemblies with Ticonal may have a pot approximately half or one-third the size which would be required by an energised speaker to give the same results. There is not only the advantage of a saving in the power required for the magnetising winding, but also there is no heat to be dissipated.

Mr. E. A. W. Spreadbury (Associate Member) :

Mr. Sowter's references to nickel iron laminations reminded me that some of them are not lacquered. It seems to me that the value of the laminations may be impaired if they are not insulated on the surface.

Mr. Sowter :

In nickel iron technique it has generally been the practice to insulate in some manner, but the tendency in wartime is to avoid lacquer, because the process involves a lot of labour. Measurements have shown that, generally speaking, for small transformers for audio-frequency voltages the oxide coating which can be produced on the nickel iron alloys is sufficiently good for the purpose. On the other hand, when building high Q chokes it is rather desirable to lacquer, for it reduces the losses probably by 10 per cent. or more. With Radiometal, Permalloy B, Rhometal and Permalloy D a good oxide coating is readily obtained, and even in the case of Mumetal it is possible to oxidise to some extent. A large percentage of Mumetal laminations are used to-day without lacquering.

A question I should like to put to Mr. Tyrrell is, "What are the limits of coercivity ?" Some years ago my firm was asked to make a permanent magnet material which to our amazement was to consist of aluminium 5 per cent., manganese 9 per cent. and silver 86 per cent., all non-magnetic ingredients. Although it seemed incredible at the time, we made the alloy, which had remarkable properties, details of which have since been published by the originator of the material (Potter).[11] In connection with a special form of voltmeter designed by Faus,[12] mention is made in the *J.A.I.E.E.* to two kinds of special magnet materials, one of them being the alloy to which I have just referred and having an extremely high coercivity. The figures quoted for the Potter Alloy are Hc 950, Br 2,200 and $(BH)_{max}$ 10^6. The point about such a high coercivity material is that one can have a piece $\frac{1}{16}$ in. thick and magnetise it so that there is a N pole on one side and an S pole on the other.

It is intriguing to me that one can make up permanent magnets from materials which are non-magnetic. Thus, for example, the Heusler alloys, manganese, copper and aluminium, are also highly magnetic.

There is another alloy even as good as Ticonal. It is platinum cobalt, but I do not think it can be regarded as a commercial competitor since it costs about £500 per lb.

Mr. Tyrrell :

In reply to Mr. Sowter's question, I think it should be stated that the limiting values of coercivity have not yet been reached. It is possible to obtain an increase in $(BH)_{max}$ up to 5 or 6 millions or even a little more on random samples of Ticonal, but no doubt the composition will have to be altered to effect further radical improvements.

There does not appear to be any practical reason why the $(BH)_{max}$ of future magnetic alloys should not be of a higher order, the value of B_r being proportionally increased.

Mr. W. Dalton (Associate Member) :

Text books and other references refer to the crystal axis of an alloy, and I have often wondered what that means. Does it mean the lines along which the crystals or iron or of iron plus something else will form ?

Mr. Sowter :

As mentioned previously, if one considers a single cubic crystal the magnetic properties vary with the direction of the applied magnetising force and the highest permeability is found along certain axes of the cube. A nickel iron alloy consists of a large number of such cubic crystals, and if absolutely regular arrangement of cubes could be obtained so that equivalent axes are in alignment, the maximum possible permeability would result in certain directions. In practice, the cubes form small colonies which we observe as visible crystals where the majority of the cubes have aligned axes, so that there is, in effect, certain directions along which optimum properties pertain. These we may call the crystal axes. The influence of cold working is to force the crystals into alignment so that there is a general tendency for the axes to be in the direction of rolling, but even under best conditions only a proportion is correctly aligned. It is possible by certain methods to estimate the general direction of the axes of the crystals, particularly with such a material as cold worked Mumetal.

Mr. Dalton :

When there is, say, 3 per cent. of chromium present, where does it go ?

Mr. Sowter :

One hears reference from time to time to the inter-atomic spaces or inter-molecular spaces of a crystal lattice, and the chromium will fit into those spaces.

A Speaker :

What is the " Barkhausen effect " ?

Mr. Sowter :

When one applies a magnetising force to a magnetic material it is usual to draw a smooth B.H. loop, and to say that it indicates the manner in which B changes with H. Barkhausen discovered that, instead of the curve being smooth, there was a series of jumps in B within a certain low region, up to about 2,000 gauss. That is the Barkhausen effect which is ascribed to the change of direction of magnetic domains. Since there are sudden changes of B, they can be converted into electrical voltages and be made audible in a telephone earpiece.

In addition to the Barkhausen effect associated with silicon alloys, there is a region, up to B=2,000, over which there are peculiar magnetic properties. When standardisation of incremental permeability testing was being discussed, it was pointed out by Webb[13] that if one gives silicon iron a mechanical or magnetic shock, i.e. by dropping it or applying a high value of H, the region of the curve up to B=2,000 will be unstable, and some two or three weeks may elapse before the material will revert to its original value. If one takes measurements before and after such a shock, the variation in permeability over this region may be as much as 300 per cent. It might appear that this " slow time change " and the Barkhausen effect are associated.

Mr. Percy G. West (Associate Member) :

How do the new magnet materials withstand vibrations and general handling ?

Mr. Tyrrell :

Magnets made of these new materials have been subjected to severe vibration for periods of over 1,000 hours and their magnetism has been reduced only by about 2½ per cent. Magnets without external iron circuits can be partially de-magnetised by pressing the like poles together, or by intermittent contact over their surfaces with permeable objects. As the result of this treatment they may lose 40 or 50 per cent. of their flux. If the materials under discussion are in an iron circuit, they are among the most stable alloys obtainable.

Mr. Ralph L. West (Associate Member) :

Will an alloy with a higher permeability than another withstand more mishandling ?

Mr. Tyrrell :

The coercive force is the important factor. Steels with higher coercive force tend to be more stable in every way. The new alloys will withstand more mishandling than the others.

Mr. A. G. P. Mower (Associate) :

One remembers the classic method of measuring lines of force or the directions of lines of force by means of filings. Has there been an improvement of that method ?

Mr. Tyrrell :

I must confess that it is a method which I still use.

Mr. Sowter :

There is a method of detecting cracks on steel shafts and castings, involving the use of a magnetic powder suspended in oil. I wonder if this can be utilised for detecting flux distribution of magnets ?

Mr. Phillips :

There is the Bismuth spiral, which is a very academic method. The spiral, placed across a magnetic field, has an increase in resistance according to the field strength. It can be used for detection, but of course will not give direction.

A Speaker :

This new permanent alloy is stated to have a high performance when operated in one direction, and a very much reduced performance when operated in other directions.

Is there a critical operating angle past which the performance suddenly drops, and if so, how wide is this angle ?

Also, if the direction of operation is important, presumably the polarity is even more important ?

Mr. Tyrrell :

The performance of Ticonal varies in a somewhat sinusoidal manner as the direction of operation deviates from the predetermined or preferred axis, as it is usually termed.

If the remanence, coercive force and $(BH)_{max}$ are plotted against the direction of operation, a series of polar diagrams is obtained. Figs. 14 and 15 show the results obtained from typical samples of Ticonal. These diagrams answer the last part of this question, as it can be seen that the direction is very important and the magnet should always be operated on its preferred axis, but it is not necessary to observe the polarity employed during manufacture. When in use the magnet may be magnetised in either direction along its preferred axis, and the direction of magnetisation may be completely reversed without reduction of magnetic properties.

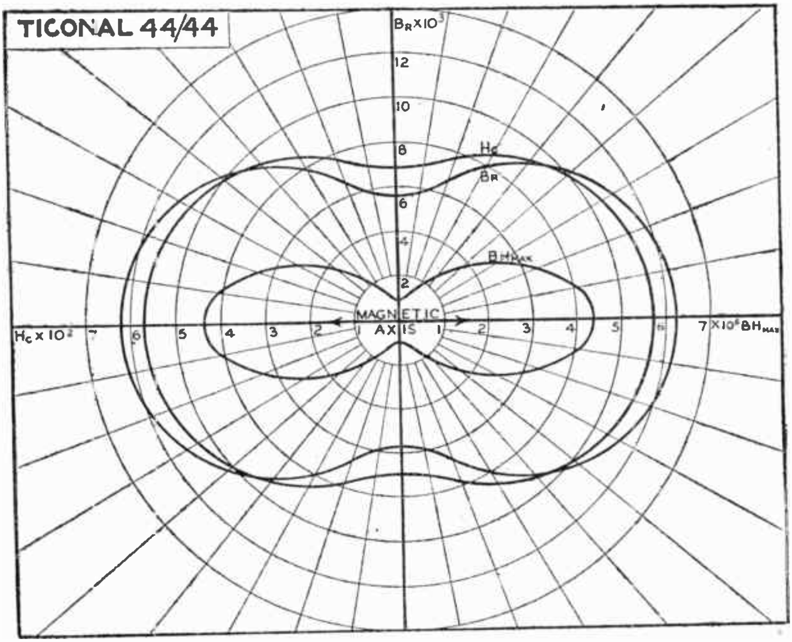

Fig. 14.

Figs. 14 *and* 15 *show the reduction in magnetic properties of Ticonal* 44/44 *and Ticonal* 42/50 *as the operating flux deviates from the magnetic axis.*

DISCUSSION

A Speaker:

Some magnetic effect has been utilised a long time ago, I think, for the operation of a microphone.

Mr. Sowter:

You are probably thinking of the magnetostriction effect. When magnetic materials are magnetised, they alter their dimensions and may become larger or smaller. Mumetal has nearly zero magnetostriction but, on the other hand, there are nickel iron compositions having quite high magnetostriction which are used for such purposes as magnetostriction oscillators. Many years ago Denman demonstrated a loudspeaker with a long length of a nickel iron wire inside a coil and attached to a diaphragm which reproduced music from 2 LO. It was very squeaky due to the limited excursion of the diaphragm at low frequencies.

A Speaker:

I remember calculating that, for a loudspeaker, I should want 250 inches of pure nickel.

Mr. Sowter:

You could have used something comparable with pure nickel, i.e. a 36 or 38 per cent, nickel/iron with a very high magnetostriction, but it should be remembered that magnetostriction varies considerably with the magnetising force applied.

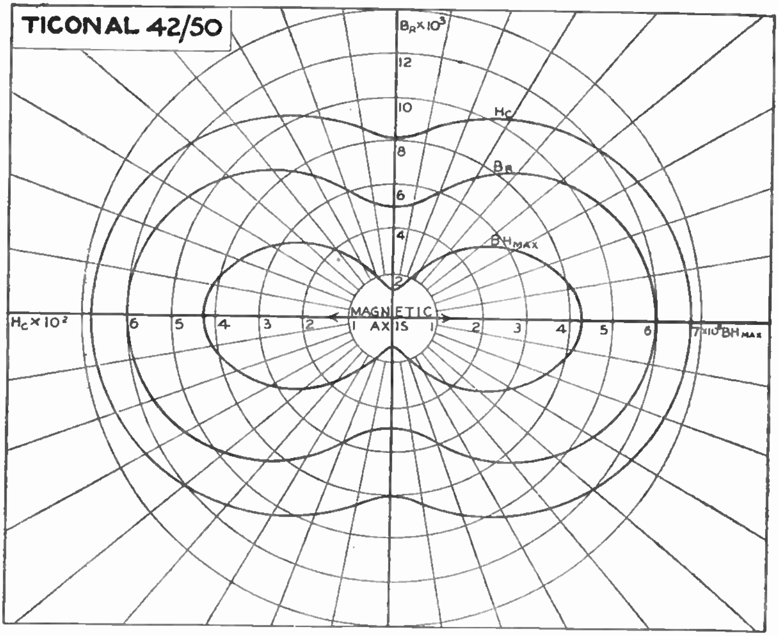

Fig. 15.

Mr. F. E. Lane:

Figures from America have been quoted concerning the ageing of permanent magnets. I wondered whether those figures related to material which had not been in use and, if so, whether Mr. Tyrrell has information available concerning material which has been in use. I should also like to know whether the nickel irons vary after they have been in use and subjected to the influence of other magnetic fields.

Mr. Tyrrell:

The figures from America relate to tests on magnets working under their correct load, that is, working on the optimum point on the demagnetisation or BH curve.

Mr. F. E. Lane (Associate Member):

Would you obtain the same results from samples which were not put to use, but which were merely placed on a shelf and subjected to tests from time to time in order to ascertain the effects of ageing ?

Mr. Tyrrell:

The results should be identical, and the tests were made with a view to ascertaining that the figures were representative of the sort of ageing to be expected in meter magnets and other apparatus in which this material is used.

Mr. Sowter:

So far as I am aware nickel iron does not deteriorate with age. It is impossible to damage magnetically the most delicate nickel iron, i.e. Mumetal. One can apply an H as high as 3,000 oersteds which is enormous, and then de-magnetise the material and find that it is quite unchanged. If it is demagnetised incorrectly it may be somewhat remanent and I am reminded that Dr. E. Hughes, of the Brighton Technical College, showed some years ago a delightful series of asymmetric hysteresis loops due to Mumetal being magnetised merely by switching off at the right moment the current from an A.C. supply.

The meeting closed with a vote of thanks to Messrs. Sowter and Tyrrell.

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The
British Institution of Radio Engineers

THEORY OF UNITS

by

L. H. Bedford, O.B.E., M.A., B.Sc. (Member)*

Appendix 2

This appendix is written to correct an error which occurs in the main paper (page 96, Vol. 3 (new series) No. 3, 1942-1943) and also to give a better account of the Giorgi System.

In the system, line 10 of Table 2, which I called " Ultra-Rationalised," the units for flux and flux density were given as $16\pi^2$ Weber and $16\pi^2$ Weber per sq. metre. The quantity $16\pi^2$ occurs in error and should be replaced by unity. The system is thus seen to be, in fact, identical with the commonly called "Rationalised Giorgi System." The constants ϵ_0 and μ_0 occurring in that system are identical with my quantities $\frac{1}{4\pi k_1}$ and $\frac{1}{4\pi k_2}$.

When writing the paper I did not notice that the Heaviside-Lorentz system of rationalised units, Line 4 of Table 2, automatically complies with the condition which I called " Ultra-Rationalisation," namely the choice of constant k_3 as $4\pi k_2$. A better presentation is obtained if we abandon the term " Ultra Rationalisation " and state that the condition $k_3=4\pi k_2$ is to constitute the prime condition of a rationalised system. In these circumstances, the constant k_3 vanishes from the scheme ; Maxwell's restriction becomes

$$\frac{k_4^2}{16\pi^2 k_1 k_2} = \frac{1}{c^2}$$

and the Ampere and Faraday relations become

$$circ\ \mathbf{H}=k_4\,\mathrm{I}$$

$$circ\ \mathbf{E}=-k_4\,\dot{\Phi}$$

Poynting's vector becomes $\frac{1}{k_4}$ [EH] and Z_0, the intrinsic impedance of free space, becomes $k_4\sqrt{\frac{k_1}{k_2}}$.

These important simplifications all follow from the single step of making $k_3=4\pi k_2$, the step which we now call rationalisation.

A further obvious simplification is to make $k_4=1$, a step which we can take without loss of generality. We are then left with one degree of freedom for the disposal of the constants k_1 and k_2. For a system referring to metres, 10^5—dynes and seconds as mechanical units, the stipulation of a single electrical unit defines the whole system. In the simplest terms we may, for instance, specify the Coulomb by choosing k_1 as $10^{-7}\ c'^2$. Alternatively, in line with the school of thought which favours the Ohm as the fundamental unit, we may specify this as $\frac{1}{120\pi}$ × the impedance of free space ! In either case, all the other units of the Practical System follow, k_2 taking the value $\frac{1}{16\pi^1}\ 10^7$. We thus reach Line 10 of the table, the Rationalised Giorgi System. What is the unit of magnetic flux in this system?

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* A. C. Cossor, Ltd.

The dimensions of flux being $F^{\frac{1}{2}} L k_2^{\frac{1}{2}} k_3^{-1}$, the magnitude of the unit in any systems based on a single set of mechanical units is dependent only on the product $k_2^{\frac{1}{2}} k_3^{-1}$. This product is seen to take the value $10^{-\frac{1}{2}}$ in lines 8, 9 and 10 of Table 2. Hence one single flux unit applies to these three systems, and this is recognised from Line 8 as being the Weber.

If we temporarily revert to the use of the term " Rationalisation " in the sense of manœuvring the quantity 4π, it will be seen by reference to Table 1 that the quantities k_1 and k_2 occur mostly as $4\pi k_1$ and $4\pi k_2$. Thus the notation itself can stand rationalising, and this has been done by christening $\frac{1}{4\pi k_1}$ as ϵ_0 and $\frac{1}{4\pi k_2}$ as μ_0. If it is preferred to adopt this notation, which in practice has a good deal to recommend it, Lines 4 and 10 of Table 2 become

	System	Mech. Units :— L	F	T	ϵ_0	μ_0	k_4
(4)	Heaviside-Lorentz	cm	dyne	sec	1	1	$1/c$
(10)	Rationalised Giorgi	m	10^5dyne	sec	$\frac{1}{4\pi}\ 10^7\ c'^2$	$4\pi\ 10^{-7}$	1

It is to be noted that all the above tabulation refers only to rationalised systems in which $k_3 = 4\pi k_2$, so that it is not possible to reproduce the whole of Table 2 in this notation. Again, with this restriction, one may construct a modified form of Table 1, as follows :—

(1)	$F = \frac{1}{4\pi\epsilon_0} qq'/r^2$	
(2)	$E = -\frac{1}{4\pi\epsilon_0} q \, grad \frac{1}{r}$	
(5)	$V = \frac{1}{4\pi\epsilon_0} \frac{q}{r}$	
(7)	$V = \frac{1}{4\pi\epsilon_0} \left(M_e \, grad \frac{1}{r}\right)$	$U = \frac{1}{4\pi\mu_0} \left(M_m \, grad \frac{1}{r}\right)$
(12)	$div \, E = \frac{1}{\epsilon_0} (\rho - div \, P_e)$	$div \, H = -\frac{1}{\mu_0} div \, P_m$
(13)	$D = \epsilon_0 E + P_e$	$B = \mu_0 H + P_m$
(14)	$W''' = \frac{1}{2} \epsilon_0 E^2$	$W''' = \frac{1}{2} \mu_0 H^2$
(15)	$circ \; H = k_4 I$ (Ampere)	
(16)	$circ \; E = -k_4 \dot{\Phi}$ (Faraday)	
	$W'' = \frac{1}{k_4} [EH]$ (Poynting)	
	$Z_0 = k_4 \sqrt{\frac{\mu_0}{\epsilon_0}}$ (Schelkunoff)	
(17)	$c_0 = \frac{1}{k_4 \sqrt{\epsilon_0 \mu_0}}$ (Maxwell)	

The

British Institution of Radio Engineers

APPLICATION OF NEGATIVE FEEDBACK TO DESIGN PRINCIPLES

by

S. Hill, M.Eng.*

A paper read before the London Section on May 26th, 1943 and before the Midland Section on September 10th, 1943.

Introduction

Negative feedback is a device whereby the performance of an amplifier is improved by coupling the output and input through a suitable network. The principal advantages are:

(1) The frequency characteristic is improved.
(2) The gain is less susceptible to variation with change in supply voltage and various other factors.
(3) The harmonic content is improved.
(4) Desirable changes in the output and input impedance can be easily effected.
(5) Noise in the later stages of an amplifier can be reduced.

The simple theory of negative feedback which leads to the familiar formulæ for reduction of gain, and consequent improvement in certain desirable features of an amplifier, bears much the same relation to the more general study of stability under regenerative conditions as exists between steady state and transient theory. The former involves only simple algebra; the latter is best studied by Fourier integrals or related mathematics of the type used so successfully by Bromwich and others to represent discontinuous functions. The first part of the theory may be easily set forth; its practical results may be visualised in physical form and apprehended by the practising radio engineer. Little more indeed is needed for the design of the audio portion of a receiving set. However, regenerative principles find their most useful application in the design of wide band high frequency amplifiers. For such design problems a wider study is essential, but the necessary mathematical theory, though its broad lines may be indicated here, must be studied in the various classical papers devoted to the subject.

The Elementary Theory

If μ and β be simple numerical ratios characterising the voltage amplifications of the amplifier and the feedback path respectively at a particular frequency (Fig. 1), the overall gain is easily shown to be $\frac{\mu}{1+\mu\beta}$, which tends to $\frac{1}{\beta}$ for a sufficiently large value of $\mu\beta$. This is the fundamental formula for negative feedback. The disappearance of μ when $\mu\beta$ is large shows at once the source of the increased gain stability.

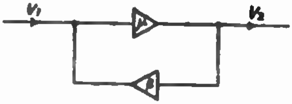

Fig. 1.—Basic principle of negative feedback.

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APPLICATION OF NEGATIVE FEEDBACK

Some "Pictorial" consequences of the fundamental formula will be of interest. The most obvious way of reducing the gain of an amplifier is by inserting a resistance potentiometer, i.e. a volume control. Such a device will reduce noise, or other spurious terms of the response, which enter before the volume control to the same extent as the signal, so that if now the signal input be suitably increased until the original output is restored, an improved signal to noise ratio will be achieved. As a means of reducing noise, negative feedback may be regarded as equivalent to a volume control of ratio $\frac{1}{1 + \mu\beta}$ inserted at some point of the amplifier beyond where the noise enters. If this point is sufficiently early in the amplifier, there is no special advantage in reducing the gain by feedback. However, where noise enters in the final stage, a potentiometer between amplifier and load may be impracticable because of the reduction in power output produced. Here the effect of feedback may be visualised by splitting the last valve, in imagination, into two parts, of which the first has unlimited output and carries the noise components, and the second is the normal output valve less the noise. Feedback achieves the effect of inserting a volume control at the physically inaccessible junction of the two imaginary components. The reduction of harmonic distortion in an output stage may be somewhat similarly visualised.

The reduction in output impedance due to (voltage) feedback may be understood very simply by remembering that if the gain is substantially independent of the μ path, a shunt may be applied to the output terminals without appreciably changing the output voltage. This is clearly equivalent to a reduction of output impedance and similar reasoning may be applied to show that the input impedance is similarly lowered. It must be borne in mind, however, that although a low impedance shunt across the output terminals may not greatly reduce the output voltage there will be an increase in harmonic content, and this fact must be taken into account in designing the output transformer for a feedback amplifier when this is external to the feedback path. In general the shunt reactance of the transformer should not be allowed to fall, in the useful range, to values which would be inappropriate if it were applied to the amplifier without feedback.

Types of Feedback

Feedback consists essentially of introducing into the input circuit a signal derived from the output circuit. This may be achieved in various ways and will lead to a variety of different gain characteristics and different input and output impedance characteristics. Some of these different back couplings will be briefly considered.

Broadly speaking, there are two ways in which a feedback signal may be derived from the output circuit, and two ways in which this signal may be applied to the input circuit, and these may be combined in various ways. Taking first the output circuit, a feedback voltage may be made dependent either (a) on the voltage appearing across the load impedance, or

(b) on the current flowing through the load impedance.

The first method is usually termed voltage feedback and has the effect of making the μ path output impedance less than it would be without feedback, while the second method is termed current feedback and has the effect of increasing the μ path output impedance. The fundamental formulæ for these two simple cases are derived in an appendix. An example of current feedback of special importance is the so-called cathode-follower circuit, where the output of a valve is taken from its (unshunted) cathode bias resistor. Taking next the input circuits, the same considerations evidently apply so that the feedback voltage may be injected either in series (current feedback), or in parallel (voltage feedback) with the source of signal to be applied to the input of the amplifier. Thus, for example, if the feedback signal is made dependent on the voltage across the output load and is applied in series with the source of input voltage, the type of feedback is termed " voltage-current " or alternatively " shunt-series " feedback. Other combinations yield the forms voltage-voltage, current-current and current voltage feedback.

Since current feedback either at the input or output of an amplifier results in an increase of amplifier impedance and voltage feedback produces a decrease of impedance, it is clear that various combinations of feedback types will give the designer a large measure of control of the input and output impedance characteristics of an amplifier. Such impedance-controlling combinations are widely used in practice where they are usually designated Bridge feedback.

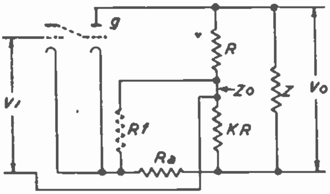

Fig. 2.—Fundamental circuit for bridge feedback.

The fundamental form of bridge is shown in Fig. 2 in which the current feedback is obtained from the resistance R_a and the voltage feedback from a potentiometer comprising resistances R and KR across the load impedance Z. The μ-path is represented diagrammatically by the necessary electrodes of a valve combination which may consist of any odd number of stages having an overall effective mutual conductance g. By a straightforward circuit analysis, on the lines of the simple derivations in the appendix, it may be shown that the impedance Zo looking into the amplifier from the load impedance Z is given by

$$\text{Zo} = \frac{(\text{R}+\text{RK})\quad(1+\text{g R}_a)}{1+\text{g}\ (\text{R}_a + \text{KR})}$$

If g is sufficiently great, this expression simplifies to the approximation—

$$\text{Zo} = \frac{\text{R}_a\ (\text{R}+\text{KR})}{\text{R}_a + \text{KR}}$$

The interesting result follows that given a sufficiently large gain, i.e. if g is sufficiently great, the output impedance of the amplifier becomes independent of the μ path, i.e. of the performance of the valves, and depends solely on the three arms of the bridge, R, KR, and R_a. Stability questions aside, it becomes possible to obtain any desired impedance and to have this impedance independent of the detailed performance of the valves. A terse way of expressing the above results is to say that, with large feedback, the bridge is always dynamically balanced irrespective of whether or not it may be passively balanced. A further advantage of the use of an output bridge is that the feedback ratio may be altered by introducing a variable resistance shunt across the feedback diagonal of the bridge. Thus consider the circuit shown above, with the addition of a variable resistance R_f shunted between the cathode and the junction of R and KR. Again it may easily be shown that when the feedback is large the voltage gain is given by

$$\frac{\text{V}_o}{\text{V}_1} = \frac{\text{ZR}\ [(\text{R}_a + \text{KR}) + \text{R}\ \ (1 + \text{K})]}{\text{R}_f\,[\text{R}_a\,(\text{R} + \text{KR}) + \text{Z}\,(\text{R}_a + \text{KR})]}$$

and the impedance looking back into the output terminals by

$$Z_o = \frac{R_a(R + KR)}{R_a + KR}$$

It will be seen that the impedance Z_o remains unchanged by the addition of R_f, and further if Z is made equal to Z_o then V_o/V_1 reduces to the simple expression

$$\frac{V_o}{V_1} = \frac{Z_o}{2R_a} + \frac{R}{2R_f}$$

It is clear that the gain of the amplifier may be changed, without in any way affecting the output impedance, simply by varying R_f.

Using the above formulæ a designer may design a variable gain amplifier whose performance in respect of gain and impedance is independent of the path, depending only on bridge components which may be held to a very high degree of constancy. The foregoing considerations show that negative feedback provides the unique facility of being able to work the output valve into its optimum load impedance while retaining the impedance looking back into the amplifier at any desired value.

It has been stated that bridge feedback may be considered as composed of current and voltage feedback combined so as to give certain unique facilities. It will be obvious that many more complicated arrangements could be devised and it will be useful to consider one or two of the more interesting of these. It will be appreciated that although bridge arms made up of pure resistances have so far been considered, it is possible, and in most designs necessary, that one or more arms be reactive. Thus to take a simple example, if R_f in the formulæ quoted above be made frequency selective, we can at once obtain an amplifier whose gain frequency curve varies in any desired manner while at the same time holding the impedance constant. This facility has useful applications in designing equalisers for programme cables and in correcting transformer losses. The simple formulæ would seem to indicate that any desired degree of equalisation could be obtained, but in practice this is not so owing to the difficulty of meeting the necessary stability conditions. Practical circuits giving a large degree of equalisation tend to become very complicated, but the basic principles are similar to those described above. Similarly it would be possible, by making certain of the bridge components frequency-selective, to obtain an amplifier whose impedance varied with frequency in any desired manner. This facility might be used to design an amplifier which would match a cable having a variable impedance characteristic. Still another obvious modification of the familiar bridge arrangement is to obtain the voltage feedback from a tapping on the output transformer or from a third winding instead of using the resistance potentiometer shown in Fig. 2.

An interesting application of the combination of voltage current and current voltage feedback is described in Brit. Pat. No. 493671, which shows how one may design a so-called transparent amplifier. Consider the circuit shown in Fig. 3. Using definitions sufficiently clearly indicated in the diagram it can be shown that, if the feedback is large—

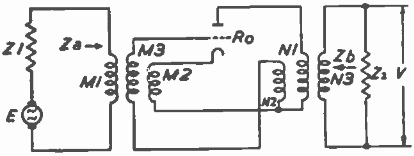

Fig. 3.—Circuit of a transparent amplifier.

$$Z_a = \frac{Z_2 \left(\frac{n_1}{n_3}\right)^2 \frac{n_2}{n_1}}{\left(\frac{m_2}{m_1}\right)^2 \left(1 + \frac{m_3}{m_2}\right)}$$

If the quantities n and m be so chosen as to make the expression involving turns ratio equal to unity, i.e. with suitable design of input and output transformers, this expression can be made to reduce to $Z_a = Z_2$. Similarly, with the same assumptions, it can be shown that $Z_b = Z_1$. Thus we have an amplifier whose input and output impedances are determined by the output and input terminations. The amplifier, in fact, exhibits the property of impedance transparency in the same way as the familiar T or π matching pads of telephone technique, i.e. looking into the input or into the output terminals one sees the same impedance as if the amplifier were removed. It can also be shown that under the same conditions, i.e. feedback large and n and m properly chosen, the gain is given by

$$\frac{V}{E} = \frac{\frac{n_1}{n_3} \frac{m_1}{m_2} Z_2}{Z_1 + Z_2}$$

Since the gain without the amplifier and its associated feedback circuit is $\frac{Z_2}{Z_1 + Z_2}$, the gain has been altered in the ratio $\frac{n_1}{n_3} \frac{m_1}{m_2}$ and is independent of frequency. Also, since the quantity $\frac{n_1}{n_3} \frac{m_1}{m_2}$ is not uniquely determined by the conditions laid down, it is possible to impose further design requirements.

A useful method of applying negative feedback which leads to many interesting results is by means of the familiar hybrid coil of telephone practice. A common arrangement is that shown in Fig. 4. The general operation will be obvious from the circuit diagram. The effect of feedback on the hybrid coils is to tend towards a dynamic balance. Considering the input coil, the current feedback from the β circuit, if sufficiently large, will reduce the flux in the grid coil (n_3) by a factor $\frac{1}{1 + \mu\beta}$ and the voltage across the terminals 1, 2 compared with the input e.m.f., E, will approach zero. Hence it can be shown that the amplifier input impedance Z_o, is given by $Z_o = \left(1 + \frac{n_1}{n_2}\right) Z_n$. Thus the amplifier impedance is determined solely by the network impedance Z_n and the turns ratio n_1/n_2. This property is extremely valuable where it is required that the amplifier impedance shall be held to accurate limits, since these limits are determined by the accuracy which can be imposed on the components of the network. Further, if the network be made variable, the amplifier impedance may be made to vary over a wide range. In this type of amplifier the loss in the output circuit may be reduced to a very low value by using hybrid coils of unequal ratios. With the more usual equal ratios this loss is of course 3 dB. Gain control may be achieved by constructing the β network as a variable T-pad equaliser. Phase correction for both low and high frequency ranges may conveniently be incorporated

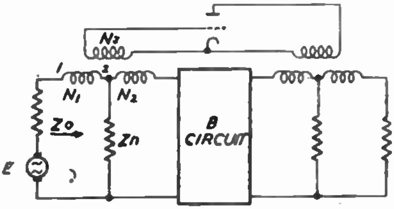

Fig. 4.—Negative feedback applied through hybrid coils.

in this pad which will take the form shown in Fig. 5. Here condenser C_1 will operate at high frequencies and C_2 at low frequencies to reduce the slope of the $\mu\beta$ characteristic and prevent a too rapid fall of gain outside the useful range of the amplifier. It will be shown later that a slow and substantially uniform fall of gain is essential if the amplifier is to be stable.

In the preceding examples there has been a single feedback path, but it is worth noting that it is possible to have a number of such paths operating over different portions of the amplifier. Two arrangements involving a double path, one within the other, are shown in Fig. 6 and other arrangements can obviously be devised. For convenience, the forward path is shown split up into separate portions having amplification factors $\mu_1\ \mu_2\ \mu_3\ \ldots$. The gains may be expressed respectively by $\dfrac{\mu_1\,\mu_2}{1+\mu_2\,\beta_2+\mu_1\,\mu_2\,\beta_{12}}$ and $\dfrac{\mu_1\,\mu_2\,\mu_3}{1+\mu_2\,\beta_2+\mu_1\,\mu_2\,\mu_3\,\beta_{13}}$. The formulæ are easily extended. It will be seen that to make the gain independent of the forward path it is necessary that $\mu_1\,\mu_2\,\beta_{12}$ or $\mu_1\,\mu_2\,\mu_3\,\beta_{13}$ shall be large compared with $1+\mu_2\,\beta_2$. Multiple feedback paths are of service in helping to ease the stability problem. In general terms it is easier to achieve phase correction in the main feedback path if the first and possibly the last stage have separate feedback paths.

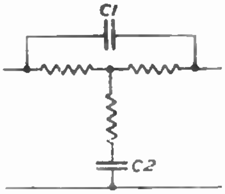

Fig. 5.—Variable T-pad equaliser.

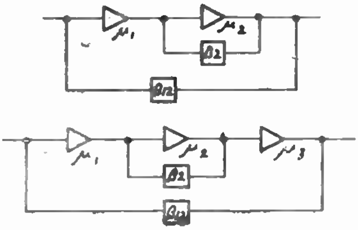

Fig. 6.—Two types of multiple-path feedback amplifiers.

The problem of stability

The term negative feedback assumes phase opposition at all frequencies between the input and the feedback voltages. The coupling elements between stages, however, introduce phase shifts which are functions of frequency and may produce a condition of instability at one or more frequencies. In a classical paper Nyquist investigated the criterion for stability by applying to the input an arbitrary function of time $f_0(t)$ analysed in terms of a fourier integral :

$$f_0(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} e^{j\omega t}\,d\omega \int_{-\infty}^{\infty} e^{-j\omega t}\,f_0(t)\,dt$$

After traversing the amplifier and feedback paths a function $f_0(t)\mu\beta(\omega) = f_1(t)$ arrives at the input terminals, $\mu\beta(\omega)$ being now a complex operator modifying the magnitude and phase of any operand to which it is applied. By considering n such traverses round the circuit a series of terms $\sum_0^\infty f_n(t)$ is obtained for the total input voltage. If this series tends to infinity as t increases even if $f_o(t)$ remains finite or dies away, the feedback system will be unstable. A somewhat simpler treatment given by D. G. Reid consists in determining the normal modes of vibration for a back-coupled system with one way transmission. The criterion for a maintained oscillation is then that one or more of the generalised angular velocities of the system shall have a positive real portion. Both treatments lead to Nyquist's rule which is of fundamental importance for design viz. : Plot plus and minus the imaginary part of the operator $\mu\beta(\omega)$ against the real part for all frequencies from 0 to ∞. If the point $1 + j(o)$ lies completely outside this curve the system is stable ; if not it is unstable. The problem of achieving any specific design is largely one of meeting the Nyquist condition. This is often a matter of considerable difficulty. Any coupling network may be reduced to a band-pass filter whose phase shift will reach 90° at some extreme frequency, and therefore if there are more than two stages an amplifier, in the absence of special precautions, will be capable of oscillation in at least one mode. Clearly the difficulty will increase greatly with the number of stages. Corrective circuits must then be applied to change the phase in the neighbourhood of the point $1 + j(o)$ on the diagram. Thus a measure of control can be obtained by a single inductance shunted across the feedback path, though this would only be adequate for a simple case. It might seem natural to obtain stability by reducing the gain rapidly immediately outside the useful frequency range, but this cannot be done without introcucing prohibitive phase shifts. There is a fixed relation between the attenuation A and the minimum obtainable phase shift B. Bode expresses the relation in the forms

$$B(f_c) = \frac{1}{\pi}\int_{-\infty}^{+\infty} \frac{dA}{du} \text{ Log Coth } \frac{|u|}{2}\, du \quad \ldots\ldots\ldots\ldots\ldots \quad (x)$$

$$\text{and,} \quad \int_{-\infty}^{+\infty} B du = \frac{\pi}{2}\,(A_\infty - A_o) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (y)$$

where $B(f_c)$ is the phase shift at an arbitrary frequency f_c.

A_∞, A_o are attenuations in nepers at infinite and zero frequencies and u is the frequency on a logarithm scale, i.e. we may write

$$u = \log f/f_c$$

From these relations he shows that, above the useful range, the gain of a feedback amplifier should fall off substantially uniformly at a rate of some 12 dB per octave. Under these conditions the phase shift approaches 180° only at extremely high frequencies where the gain will have fallen to zero. Such an amplifier, though not commercially satisfactory owing to the absence of any working margin, is nevertheless theoretically stable. It is, moreover, " absolutely " stable, i.e. it has a Nyquist diagram of the general type shown in Fig. 8A as opposed to that shown in Fig. 8B

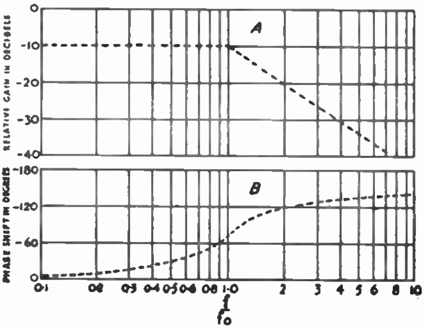

Fig. 7.—Bode's diagrams.

which represents the so-called "conditionally" stable amplifier whose curve could be made to enclose the point $1 + j(o)$, by a simple reduction in scale (i.e. by reducing the overall gain).

Imaginary nyquist diagrams.

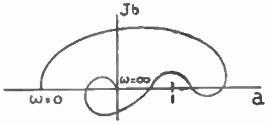

Fig. 8a.—"*Absolutely*" *stable.*

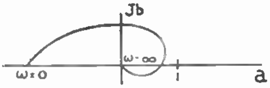

Fig. 8b.—"*Conditionally*" *stable.*

Since the considerations given above bear directly on the problem of the specific design of an actual amplifier, some further explanation of the principles seems desirable. For a full treatment Bodé's paper should be consulted.

It can be shown that the following formula holds

$$\int_{o}^{f_o} \frac{A\,df}{\sqrt{f_o^2 - f^2}\,(f^2 - f_c^2)} + \int_{f_o}^{\infty} \frac{B\,df}{\sqrt{f^2 - f_o^2}\,(f^2 - f_c^2)} = \frac{\pi B(f_c)}{2f\sqrt{f_o^2 - f_c^2}} \quad \text{when } f_c < f_o$$

$$= \frac{-\pi A(f_c)}{2f_c\sqrt{f_c^2 - f_o^2}} \quad \text{when } f_c > f_o$$

where f_o is some arbitrarily chosen frequency such as the upper limit of the useful range of the amplifier. This enables the amplitude and (minimum) phase characteristics to be plotted against f_c over the whole frequency range if the attenuation in the useful band and the phase shift above the band are specified arbitrarily. Thus we may specify $A = K$ in the useful band (corresponding to uniform amplification) and $B = k\pi/2$ beyond this range. where K and k are constants. The amplitude and phase characteristics may be plotted against $\frac{f}{f_o}$ as abscissa computed from the formula

$$A + jB = K + k\text{Log}\left[\sqrt{1 - \frac{f^2}{f_o^2}} + j\frac{f}{f_o}\right]$$

where the real and imaginary parts on both sides correspond to the attenuation and phase characteristics respectively. Although it is only necessary (for absolute stability) that B should not reach 180° a more economical design with a greater permitted maximum feedback results if the phase remains within a fixed safety margin (say 30°) of 180° throughout the upper range. We may therefore put $k = 1{\cdot}67$ and obtain the curves shown in Fig. 9. For comparison, Fig. 7 shows the phase characteristic which results if the amplitude falls off at a uniform rate of 10 dB. per octave. It will be seen from Fig. 9 that the cut off range is one octave less than an octave per bel. of feedback. For 40 dB of feedback at least 4 octaves are necessary. Since experience shows that the straight line attenuation characteristic must be carried some 10 dB below zero gain, this gives 5 octaves or 32 times the highest useful frequency. In a high frequency amplifier this result may well lead to a physically unrealisable design. It is therefore necessary to make sure before attempting a design that the effects of stray capacities do not reduce the gain to zero before the required frequency is reached. In a less extreme case the asymptotic attenuation of the amplifier may modify the extreme tail of the attenuation characteristic and this may have a large influence on the phase characteristic. It is, however, often possible to correct this by applying a patch to the attenuation characteristic. When this proves impossible, it is necessary to reduce the feedback. When a suitable curve has been obtained it is of course necessary to design a network, using the known principles of equaliser design, which will simulate the given curve sufficiently closely to achieve the required stability under all working conditions and allowing all necessary safety factors to take care of manufacturing tolerances and variations of components with time, temperature, etc. The principles outlined have also to be applied to the lower end of the spectrum although in practice this is usually simpler.

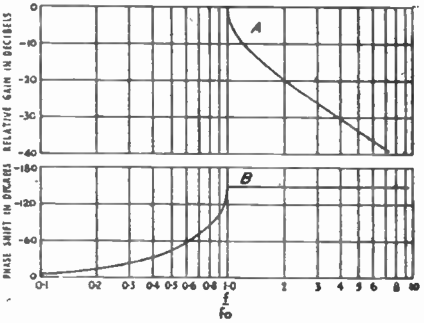

Fig. 9.
Bode's Diagrams.

Design Examples

The principles sketched in the foregoing text are now widely known. On such principles, the practising designer must build a design technique, or a code of rules of procedure, whereby he may specify in detail an amplifier which will meet a set of imposed requirements. This actual design procedure will be made clearer by considering two examples, viz. (*a*) the broad design of a fictitious three-stage amplifier and (*b*) results obtained on a four-stage audio amplifier. In (*a*) the approach is given to each of the problems the designer needs to pass under review before he can determine the actual design, but numerical results are not given, while in (*b*) a known amplifier is discussed.

Three-Stage High Frequency Amplifier

We begin by assuming the following requirements :—

(1) The gain to be 50 dB when working between impedances of 100 ohms and over a frequency range of 20 to 1.
(2) The feedback to be as large as possible and not less than 30 dB.
(3) The amplifier to be " absolutely " stable with ample commercial margins.

Fig. 10 shows the skeleton schematic in which are marked 5 important networks to be considered later in detail. The feedback is of the current type. The valves used would be high slope pentodes designed to have the least possible capacities in relation to the slope. It is first necessary to ensure that 30 dB feedback is not an impossible requirement and as a preliminary to this to estimate the frequency at which the gain falls to zero. This is often termed, not very happily, the frequency at which the asymptotic curve cuts the zero axis, or simply the asymptotic frequency. With good valves and careful design this frequency can be made very high. It is now possible, using formulæ given in Bode's paper, to calculate that 52 dB feedback is possible if no stability margins are allowed, a figure which seems satisfactorily high compared with the 30 dB requirement. The calculation, however, may be refined if definite margins be assumed. There is no fixed

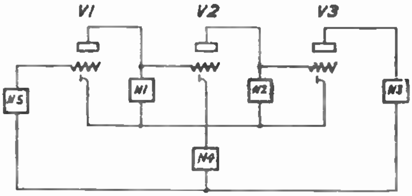

Fig. 10

rule as there are a number of variable factors, viz. the purpose of the amplifier, the limits of accuracy and stability which may be economically assigned to the components, etc. For the present example we assume fairly average margins of 30 degrees and 9 dB. This means the phase shift at the "asymptotic frequency" is 30 degrees below the danger point, 180 degrees (or 360 degrees if reckoned right round the $\mu\beta$ loop), and that the gain round the $\mu\beta$ loop is minus 9 dB at the frequency for which the phase shift reaches 180 degrees. The above figure of 52 dB is reduced to about 35 dB if allowances for these margins are made in applying the formulæ. It appears then that 30 dB feedback is consistent with the other assumptions. The gain characteristic can now be drawn in.

Two closely related steps now become necessary, viz.:

(*a*) To determine configurations for the various coupling networks N_1 to N_5 which will lead to the given $\mu\beta$ gain characteristic,

(*b*) To determine whether the valves have sufficient amplifying power to produce the required excess of forward gain over gain reduction with feedback.

It is desirable first to draw approximate equivalent circuits for the various couplings throughout the path. We shall confine ourselves to the uppermost part of the frequency spectrum as the lower end is appreciably simpler while introducing no essentially new problems. Considering then the high frequency equivalent of network N_3, we arrive at the circuit of Fig. 11A. Here i is the constant current output from the pentode V_2, C_2 is the valve output capacity, C_1 the transformer self capacity, L is transformer leakage inductance, and R the load resistance, the quantities C_1, L, and R being referred to the valve side (high side) of the output transformer. Usually the impedance of N_4 is negligibly small compared with that of the L C R combination and on this assumption an expression is easily derived for the voltage arising across N_4 per unit current, i. We have

$$\left|\frac{V}{N_4}\right| = \sqrt{\frac{(1 - n\alpha^2)^2 + \alpha^2}{[1 - n\alpha^2(1 + k)]^2 + \alpha^2(1 + k)^2}}$$

$$\text{Tan } \theta = \frac{-k\alpha}{1 - n\alpha^2)[1 - n\alpha^2(1 + k)] + \alpha^2(1 + k)}$$

where $\alpha = \omega C_1 R$

$n = L/C_1 R$

$k = C_2/C_1$

V is the voltage per unit current and has the dimensions of an impedance.

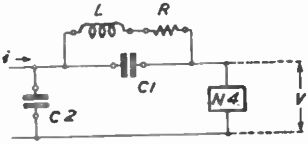

Fig. 11*a*.

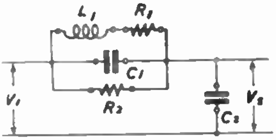

Fig. 11*b*.

At zero frequency ($\alpha = 0$) we obviously have $\left|\frac{V}{N_4}\right| = 1$ so that 20 log $\left|\frac{V}{N_4}\right|$ calculated from the above formula and plotted against α gives, in decibels, the gain at any frequency compared with that at zero frequency and tan θ gives the phase. These curves are sketched in Fig. 12 for various values of n and one value of k. The choice as to which of these curves is the most suitable, i.e. what values should be assumed, for n and k will depend on what configurations are chosen for the other networks. We may, however, note the following relations. C_1, the self capacity of the transformer, is naturally to be kept as low as possible and this seems to fix k unless the output capacity, C_2 of the valve is artificially increased. However, C_2 may be reduced by applying current feedback to the last valve. In many designs the control of k so obtained is worth the reduced gain. R is determined when n has been chosen. It should approach the optimum load for the given valve, or, if this cannot be arranged, it should at least be high enough to allow of the required output without undue harmonic distortion. This is one reason why C_1 must be small. If we determine from the required gain characteristic the fall off in gain at an assumed frequency, α is determined, and this gives another relation between C_1 and R and so fixes L for a given value of n.

We next examine the network N_5, whose high frequency equivalent is shown in Fig. 11B. Here C_2 represents the input capacity of V_1, R_2 is the resistance termination on the grid side of the transformer, R_1 is the load impedance, C_1 the self capacity, and L_1 the leakage inductance of the transformer, the last three quantities being referred to the grid side of the input transformer. The procedure is similar to that outlined for N_3 and yields a family of curves whose shape is like that of the family already sketched but modified by the presence of R_2.

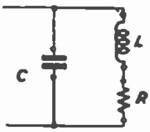

Fig. 11*c*.

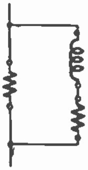

Fig. 11*d*.

Next the intervalve couplings are to be studied. The first coupling will have to be designed to prevent any appreciable fall off in gain within the useful band. It is usual, therefore, to design for a resonant peak at about the upper frequency limit. Beyond this frequency the response will fall off rapidly with a phase shift of about 90 degrees occurring comparatively early. The general type of circuit is that shown in Fig. 11C. Here C is the total valve capacity and L and R are chosen circuit elements. The impedance of this circuit, which is proportional to the voltage across it for pentode operation, is given by

$$\left|\frac{Z}{R}\right| = \sqrt{\frac{1 + n^2\alpha^2}{\alpha^2 + (n\alpha^2 - 1)^2}}$$

$$\text{Tan}\ \theta = \alpha(n - 1 - n^2\alpha^2)$$

$$\text{where } n = L/CR^2 \text{ and } \alpha = \omega.C.R.$$

The performance of the coupling may now be plotted with n as parameter. Sometimes an additional condenser is added across L to obtain a greater control of the other elements.

The coupling between V_2 and V_3 is chosen so as to introduce as little phase shift as possible near the edge of the pass-band. It is often found that a plain resistance is adequate, shunted, of course, by the unavoidable stray capacities. The value is often chosen so as to reduce the forward gain to a suitable value.

Finally we consider N_4. This network is used to control the slope of the $\mu\beta$ curve above the pass range, i.e. to prevent too rapid a decrease. It must, of course, be substantially a pure resistance over the pass range or the amplifier will have a tilted characteristic, but it may be manipulated in any desired manner above this range. A simple form is shown in Fig. 11D. More complicated configurations are sometimes required, but if excess gain is available it is often desirable to manipulate the μ path to approach the given $\mu\beta$ characteristic, leaving the β path comparatively simple.

The actual design of the networks to simulate the required $\mu\beta$ characteristic cannot be given without undue prolixity. The processes are similar to those used in designing equalisers. The common forms of the coupling networks have been given and numerical work has shown that these are adequate to cover the requirements. The work is directed to choosing the values of the variables n and k etc. The designer is guided to possibly suitable values by past experience and must make many checks by calculating the overall $\mu\beta$ characteristic and modifying the details of the couplings as the result may indicate. The process is naturally somewhat laborious.

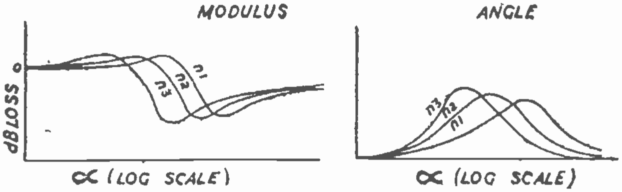

Fig. 12.

Supposing this work has been done, the designer must finally ascertain whether there is sufficient forward gain available, or if there is too much he must decide how best to reduce it. The actual values of the coupling network impedances, as distinct from the values related to zero frequency, are calculated, and are multiplied by the slopes of the valves to obtain the total gain round the $\mu\beta$ loop. In the present example the result must be at least 30dB. There should be no great difficulty with valves having a slope of say 8 milliamps per volt. If the gain should prove to be 35 dB, it may still be used as 30 dB was a minimum requirement and 35 dB was seen to be possible without reducing the assumed margins. There is always, however, the tacit assumption that the theoretical $\mu\beta$ curve has been adequately simulated. A gain greater than 35 dB will certainly call for a reduction which can be easily achieved by reducing the value of the coupling resistance between V_2 and V_3 or by applying individual feedback to one of the stages. This adjustment will affect the $\mu\beta$ characteristic to some extent and a further recheck becomes necessary.

Practical Results on a Four-Stage Amplifier

The example sketched above might find a radio application as an intermediate frequency amplifier and thus belongs to receiver technique ; the practical example now to be discussed is in sharp contrast ; it is a high-power audio amplifier used as part of a radio transmitter. The feedback achieved is quite small. No such figure as the 30 dB of the previous three-stage amplifier could be attained because of the greater number of stages and the unavoidably large phase shifts introduced by the transformer coupling. Nevertheless, this small feedback confers a very high performance on the amplifier.

The circuit is shown in Fig. 13. There are four, or in one modification five, stages of which the final pair is transformer coupled and the previous pair choke-capacity coupled, the earlier stages being resistance capacity coupled. The amplifier delivers 70 kilowatts of audio power to a Class C radio frequency amplifier where 100 kilowatts of carrier are anode modulated.

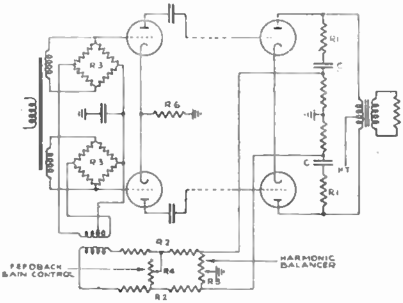

Fig. 13.—Four-stage high-power audio amplifier with voltage feedback.

Referring to Fig. 13, it will be seen that voltage feedback is used. The voltage is developed across resistance R_2 in the potentiometer formed by R_1 and R_2, the condensers C serving to isolate the direct voltage from the feedback line. Since R_1 is high compared with R_2 the circuit forms a constant current generator so that the load shunted across R_2 can be varied over quite a wide range without affecting the current in R_1. The feedback voltage is fed to the bridge networks in the grid circuit of the second low-frequency amplifying stage so that the feedback voltage in the output of this stage is developed across resistances R_3. The bridge networks are introduced to reduce the capacity of the feedback circuit across the input transformer, and hence reduce phase shift due to this transformer. Obviously a 6 dB loss of gain occurs due to their use as only half the effective signal volts are applied to the grid of the amplifier.

As the feedback line is of low impedance, a small transformer, having negligible phase shift compared with the interstage transformer, is connected at the termination to match the impedance of the bridge circuit ; this transformer also serves to reduce parallel current in the feedback line.

The feedback gain control R_4 acts to vary the terminating resistance of the potentiometer and so allows the amount of feedback to be varied, whilst the harmonic balancer R_5 permits additional feedback for the even harmonics to be obtained by adjusting the position of the centre point of the circuit about earth. A mean setting of, say, 400 and 4,000 c.p.s. is usually chosen, the improvement at the higher frequencies being quite marked.

Fig. 14 shows the gain reduction curve taken experimentally, around the complete feedback loop, the value in the mid-frequency band being 6 dBs

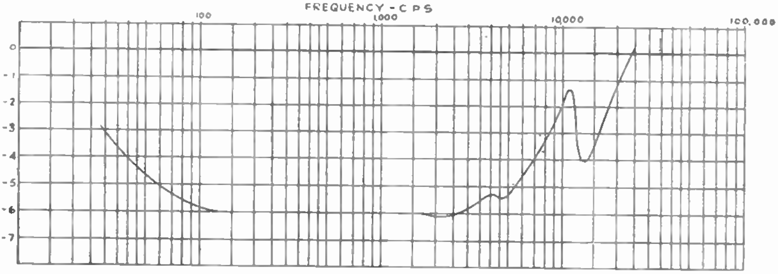

Fig. 14.—Gain reduction curve round the feedback loop.

falling to zero at about 24 kc/s. As a result the third harmonic distortion for a fundamental frequency of 8,000 c.p.s. is not reduced, and tends to be increased for higher frequencies. However, as these harmonic frequencies fall outside the received band they do not cause distortion, but they might give rise to interference in adjacent channels at high levels of modulation, In practice the average level of modulation in normal programmes falls off very rapidly at the higher frequencies and does not, for example, exceed 10 per cent. at 8,000 c.p.s., so that second channel interference is not to be expected and, in practice, is not detected.

The overall frequency response of this transmitter determined from the modulated R.F. output, for a constant audio input voltage at all frequencies—

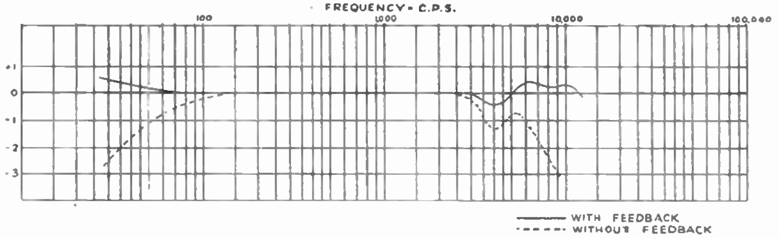

Fig. 15.—*Frequency response of* 100 *kW. transmitter.*

equivalent to a modulation depth of 50 per cent. at 1,000 c.p.s. — is shown in the full curve of Fig. 15 with feedback applied. It is seen to be substantially flat over the whole frequency range of 30 to 10,000 c.p.s., the deviation not exceeding 0.5 dB. For comparison, the response without feedback is given on the same figure.

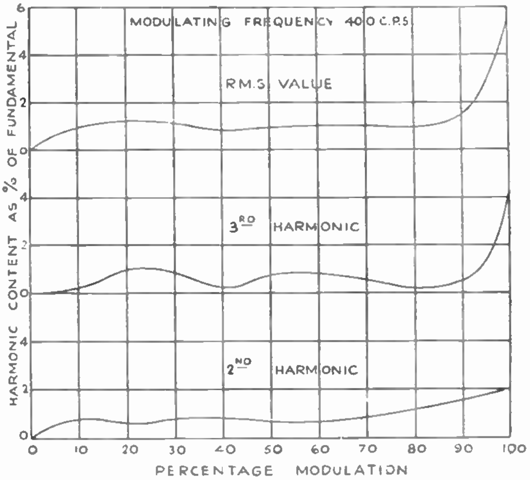

Fig. 16.—*Harmonic distortion in* 100 *kW. transmitter.*

In Fig. 16 the measured harmonic content, expressed as percentage values of the fundamental, is plotted against percentage modulation of the R.F. carrier for a modulating frequency of 400 c.p.s., and it will be seen from a study of this diagram and Fig. 15 that the fidelity of such a high-powered transmitter is of a high order. Moreover, the performance is very consistent, the characteristics measured on successive occasions on a given transmitter, and when compared between one transmitter and another similar one reproducing themselves with a high degree of precision. The noise level in the R.F. output of these transmitters is 68 dB unweighted below the level corresponding to 100 per cent. modulation.

APPENDIX

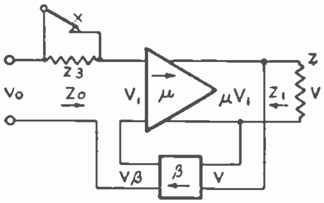

Fig. 17.

Several formulæ for gain and impedance of amplifiers with bridge feedback have been given without proof. The derivation of similar formulæ in two specially simple cases will bring out the fundamental operation of negative feedback and serve as prototypes for the derivation of the more complex formulæ. Figure 17 shows an amplifier with voltage feedback at the output terminals and current feedback at the input terminals. We may assume without loss of generality that the shunt impedance of the β path is infinite, since any impedance it may have may be supposed absorbed into the load impedance Z, and similarly we may assume that the series impedance of the β path is zero. Let V_1 be the grid cathode voltage, V_0 the input voltage and V the output voltage. Then the following equations may be written down by inspection :—

$$V_1 = V_0 - V\beta$$

$$V = \mu V_1$$

Eliminating V_1 we obtain the fundamental formula

$$V/V_0 = \mu/(1 + \mu\beta) \quad \ldots\ldots \quad (1)$$

The equivalent output impedance Z_1 may be found as follows :—By definition μ is the factor relating the line voltage V to the grid cathode voltage V_1. Let μ_2 be the factor relating the internal e.m.f. of the last stage to the same voltage, so that if Z_2 be the internal impedance of the last stage, we have

$$\mu = \mu_2 Z/(Z + Z_2) \quad \ldots\ldots \quad (2)$$

If the load Z were removed there would be a new line voltage V related to V_2 by the formula

$$V_2/V_0 = \mu_2/(1 + \mu_2\beta) \quad \ldots\ldots \quad (3)$$

derived from (1) by using the open-circuit value of μ. We may suppose V and V_2 to be related by the usual formula connecting load and open circuit voltages, viz., $V = V_2 Z/(Z + Z_1)$ where Z_1 is the required equivalent impedance. The last formula may be written $Z + Z_1 = V_2 Z/V$ which, on substituting for the voltages from (1) and (3) becomes $Z + Z_1 = \dfrac{Z\mu_2(1 + \mu\beta)}{\mu(1 + \mu_2\beta)}$

On substituting for μ in terms of μ_2 from (2) we obtain $Z_1 = Z_2/(1 + \mu_2\beta)$, showing that voltage feedback effectively decreases the internal impedance of the output stage by the factor $1 + \mu_2\beta$.

We may find the equivalent impedance looking into the input terminals by supposing a series resistance Z_3, equal to the input impedance without feedback, switched into circuit. The grid cathode voltage assumes some new value V_{12} given by $V_{12} = V_0 - \mu\beta V_{12} - Z_3 i$ where i is the input current.

This may be simplified to $V_{12} = (V_0 - Z_3 i)/(1 + \mu\beta) \ldots\ldots (4)$

But if the required equivalent input impedance be Z_0 then

$$V_{12} = V_0 \frac{Z_0}{Z_0 + Z_3} - \mu\beta\, V_{12} \quad \ldots\ldots \quad (5)$$

We also have

$$V_{12} = Z_3 i \quad \ldots\ldots \quad (6)$$

Eliminating V_{12}, i, V_0 between (4), (5) and (6) we obtain $Z_a = Z_3(1 + \mu\beta)$ showing the increase of impedance due to current feed-back.

Fig. 18A shows the simplest cathode follower circuit where the load impedance is connected in place of a bias resistor. If the valve has an amplification factor μ and an internal impedance Z_a, the grid/cathode input is $V_o - V$ and the e.m.f. developed $(V_o - V)\,\mu$. The load voltage is therefore

$$V = \frac{\mu(V_o - V)\,Z}{Z_a + Z}$$

whence

$$\frac{V}{V_o} = \frac{\mu}{1 + \mu + Z_a/Z}$$

The open circuit value of $\frac{V}{V_o}$, obtained by putting Z equal to infinity in the above expression is $\frac{V_o\mu}{1 + \mu}$ and the short circuit current I obtained by putting Z = Zero in the expression $\frac{I}{V_o} = \frac{\mu}{Z(1 + \mu + Z_a/Z)}$ is μ/Z_a. The valve may accordingly be represented by the equivalent circuit of Fig. 18B. This circuit clearly gives its maximum power into an impedance of $\frac{Z_a}{1 + \mu}$ which is approximately equal to the reciprocal of the mutual conductance $\frac{1}{g}$ if μ be large. This power is then $\frac{V_o^2 g}{4}$, which is to be compared with $\mu\,\frac{V_o^2 g}{4}$ when the valve is used normally and operated into its internal impedance Z_a.

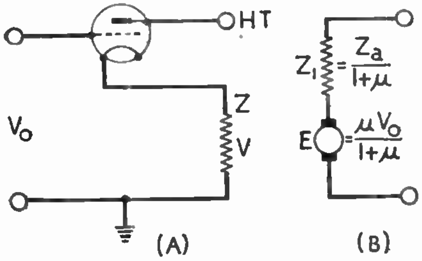

Fig. 18.

LONDON DISCUSSION

The Chairman, Mr. G. A. V. Sowter, thanking the author for his interesting paper, said that at last there was a description of the perfect amplifier. As he saw it, the characteristics of this device in a generalised form were :—

1. An amplifier principle which enabled straight-line frequency characteristics to be obtained.
2. The possibility of minimising distortion.
3. Considerable reduction of noise level.
4. Control of the phase change of the amplifier.
5. Ability to arrange for any desired tone control in upper or lower registers.
6. Amplifier unaffected by mains voltage variations.
7. Possibility of changing valves without affecting performance.
8. Control of both input and output impedance.

The author had indicated that although all these things could be done, they required a considerable amount of thought.

The paper disclosed valuable information, and in addition to the oral discussion, Mr. Hill would be very pleased to receive written communications.

Dr. N. Partridge :

The form of negative feed-back with which we are most familiar is that employed in audio-frequency amplifiers for the purpose of reducing the effective impedance of the output and of reducing distortion. The feed-back voltage is sometimes taken from the anode of the output valve, sometimes from the secondary of the output transformer and sometimes from a separate winding provided for the purpose, i.e. from points (1), (2) and (3), Fig. 19a. I propose briefly to analyse the relative merits of these three possibilities from the viewpoints of frequency, phase and harmonic distortion.

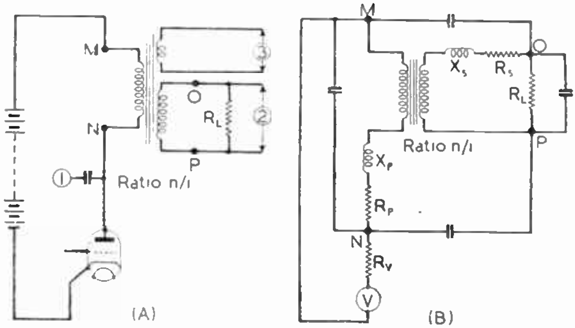

Fig. 19.

The total distortion experienced by the load R_L obviously appears at the output terminals OP or (2) Fig. 19a. Therefore, to obtain partial cancellation, this is the ideal point from which to take the feed-back voltage. The relative effectiveness of employing points (1) or (3) will depend upon how closely the wave-forms at these points approximate to that at (2).

Much work has been published concerning transformer distortion, but it should be noted that most of it, including my own, refers in fact to the stage distortion as measured from the grid of the output valve to the secondary of the output transformer. The familiar "transformer" response curve is in truth a "stage" response curve and depends as much upon the characteristics of the valve as upon the transformer. Our present object is to examine the less discussed subject of true transformer distortion as measured from the primary to the secondary terminals.

Fig. 19a can be reduced to the equivalent circuit of Fig. 19b. The resistances, leakage reactances and capacities of the windings have been localised externally, but the transformer must still be regarded as exhibiting iron losses and iron distortion. Further simplification can be introduced as shown in Fig. 20a, b and c when considering the low, medium and high audio frequencies respectively. Elements too small to produce appreciable effect are omitted and the turns ratio (originally n/1) has been reduced to unity.

Low Audio Frequencies.—With varying frequency, the ratio of the primary voltage to the secondary voltage will be proportional to the ratio of the impedance between the points M and N to that between M and P (the circuit through R_V and V

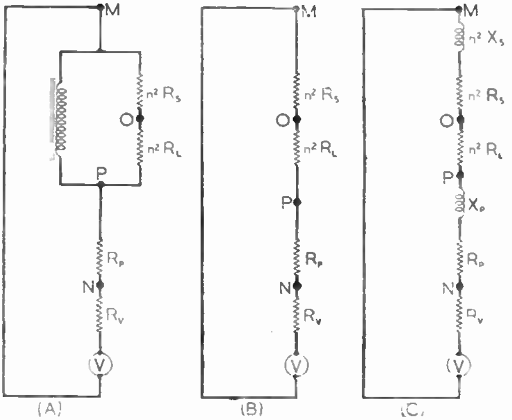

Fig. 20.

being open). At the medium frequencies this ratio remains constant and is $(n^2R_S + n^2R_L + R_P/n^2(R_S + R_L)$. At the lowest considered frequency this ratio will approach unity since the shunt impedance of the primary will fall below $n^2(R_S+R_L)$ but will remain greater than R_P (the winding resistance). Thus, providing R_P is small by comparison with $n^2(R_S+R_L)$, the ratio of primary to secondary voltage will remain approximately constant with descending frequency, and points (1), (2) and (3) Fig. 19a will be equally suitable as sources of feed-back voltage.

The phase distortion or phase shift occurring between MN and OP can be deduced by means of Fig. 21a in conjunction with Fig. 19b. The vector Φ represents the flux, e_S the induced secondary voltage and e_P the part of the voltage applied to the primary (MN) required to balance the back e.m.f. The secondary current I_S is in phase with e_S (assuming resistive load) while primary load current I'_P is equal to I_S/n^2 but is displaced by 180 deg. The total primary current I_P is given by the vector sum of the load and no-load currents, i.e. I'_P plus I_0. The voltage drop through R_P is I_PR_P and is in phase with I_P. Therefore the total applied primary voltage E_P is the sum of this drop plus e_P. Remembering that I_0 may become greater than I'_P at extreme frequencies, it will be seen that a high primary resistance will cause the secondary voltage to lead the primary voltage by an appreciable angle, after allowance has been made for phase reversal. The same phase shift will occur in the case of a separate feed-back winding. The employment of points (1) or (3) Fig. 19a will not compensate for this distortion.

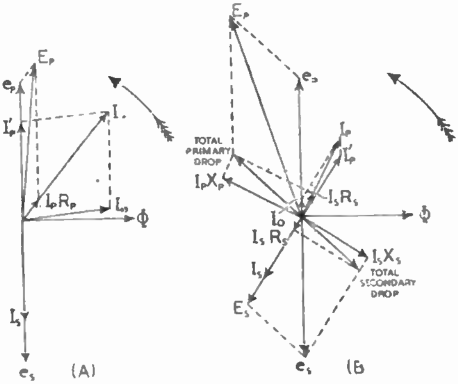

Fig. 21.

The fractional harmonic distortion caused by the magnetic material used in the core of the transformer is approximately proportional to R/Z_f at any one flux density when measured across the output terminals OP. R is the combined resistance of $n^2(R_S+R_L)$ in parallel with (R_P+R_V), and Z_f is the shunt impedance of the primary (Fig. 20a) at the fundamental frequency. Proof of this will be found in my paper on Harmonic Distortion in Audio Frequency Transformers read before this Institution on March 7th, 1942, and also in a series of articles in the " Wireless Engineer " dated September, October and November, 1942. Firstly, the application of negative feed-back, be it from points (1), (2) or (3) Fig. 19a, will reduce the *effective* value of R and thus reduce R/Z_f. Secondly, the reduced harmonic content will be further diminished by partial cancellation. Providing R_P is small by comparison with the *effective* value of R_V, approximately equivalent results will be obtained from the three alternative feed-back sources.

Medium Audio Frequencies.—The shunt impedance formed by the transformer primary is too large to cause appreciable effect while the series leakage reactances remain too small. The medium frequency band may be loosely defined as that band over which the preceding statement can be regarded as remaining approximately true. Hence the circuit behaves as if it were purely resistive. It follows that all forms of transformer distortion will be negligible. Feed-back can be taken from point (1), (2) or (3) Fig. 19a at pleasure.

High Audio Frequencies. It is apparent from Fig. 20c that the impedance between the primary terminals MN will increase with frequency. Thus the voltage across MN will rise while the current, and with it the voltage across the output OP, will fall as $(n^2X_S+X_P)$ grows larger. Thus attenuation occurs between the primary and secondary terminals and point (2) Fig. 19a is the only satisfactory source for feed-back purposes. It may be noted in passing that the employment of point (1) will tend to preserve constancy of voltage across the primary and thus prevent the rise with frequency mentioned above. This will augment the attenuation at the secondary terminals and will result in a worse state of affairs than originally existed. The employment of a separate feed-back winding falls midway between the two cases just considered. The influence of X_P will be experienced but not that of n^2X_S. The leakage reactance of the third winding will differ from that of the true secondary and its effect will depend upon the extent to which the winding is loaded.

Fig. 21b relates to the phase shift at the high audio frequencies. Φ, e_S and e_P have the same significance as above. The secondary current I_S lags behind e_S on account of X_S. The total secondary voltage drop is the vector sum of I_SR_S and I_SX_S. The secondary voltage applied to the load is given by $e_S-(I_SR_S+I_SX_S)$. As before, I'_P is in phase opposition to I_S and the total primary current is the sum of I'_P and I_0. It should be noted that the magnetising component of I_0 becomes insignificant at high frequencies. The voltage drop in the primary is the sum of I_PR_P and I_PX_P, and the voltage applied to the primary terminals is the vector sum of e_P, I_PR_P and I_PX_P. The secondary voltage thus lags behind the primary voltage (allowing for phase reversal) and partial correction can be obtained only by feeding back from the secondary terminals.

In the preceding discussion a purely resistive load has been assumed throughout. The effect of a reactive component can readily be deduced and it will be found that the value of the secondary resistance then assumes greater importance.

Mr. J. C. G. Gilbert (Member) :

The criterion of any audio-frequency design was that the effect upon listening over the air should be the same as if the person listening was in the studio, whether it be speech or music. Whilst the perfect amplifier had been obtained it was necessary to worry about two disturbing factors at each end, and the one that created the greater amount of distortion was the loudspeaker. Mr. Hill had mentioned the possibility of feed-back being applied actually to the loudspeaker speech coil, but it would still be necessary to compensate for distortion created by the diaphragm system. Had any research work been conducted by placing a known microphone in front of the diaphragm and compensate for the spurious diaphragm distortion ? Further, could the same technique be applied to the microphone system ?

Mr. Hamburger (Associate Member) :

Referring to the type of Nyquist diagram which just excluded the critical point (1,0) by making a detour round it, said that if the amplifier was forced into oscillation by impressing on the first grid an AC voltage of such amplitude (and adequate frequency) that it would overload the amplifier, were it not possible that the amplifier would remain oscillating for the simple reason that the gain had dropped due to overloading thus altering the scale of the original Nyquist diagram with respect to the critical point (1,0) until that point would find itself within the diagram ? He also enquired whether the author used general locus diagrams for finding the right type of interstage coupling circuits, since such locus diagrams rather quickly give a survey about a circuit's general behaviour.

Mr. George Wheeler (Visitor) :

The author did not make mention of the effect on the input impedance of an amplifier using feed-back, and as a matter of interest he would like to mention a problem that he had solved by the use of feed-back.

The problem was to measure an acoustic pressure with a very small capacity microphone ¾ in. in diameter. This meant an effective microphone capacity of a few m.m.f., which meant that coupling resistance and input resistance of the amplifier should be of the order of several thousand megohms, whilst the associated self capacities should be negligible. By using a valve loaded in the cathode circuit with a grid leak of 20 megohms, the input resistance was found to be over 2,000 megohms, whilst the coupling resistance normally required for polarising the microphone could be entirely omitted by utilising the voltage drop across the cathode resistance. Under these conditions satisfactory response and sensitivity was obtained with a microphone only ¾ in. in diameter. There was no need to provide a line matching transformer as the output impedance was of the order of a few hundred ohms. Again the effect of feed-back.

Mr. R. J. Cox (Student) :

There has been some discussion recently on the subject of negative feed-back oscillators, which tends to suggest that such oscillators have a remarkably high stability of characteristics.

Can these oscillators be designed by a simple modification of the methods outlined by Mr. Hill for designing amplifiers, or are totally different principles involved ?

REPLY TO LONDON DISCUSSION

Mr. S. Hill :

In reply to Mr. Gilbert, there is no fundamental objection to obtaining a distortionless air-to-air system by using an electro-acoustic feed-back path, but the stability problem seems almost insuperable because of the large and violent phase changes occurring in the loudspeaker. These changes depend, among other things, on the length of the air paths between speaker and feed-back microphone, and would alter with the microphone position and the acoustics of the listening room. If these difficulties were overcome we should use the scheme to correct the loudspeaker and not the microphone. This is because, to correct a loudspeaker, one needs an accurate microphone but one would need an accurate loudspeaker to correct the performance of a microphone in this way.

The answer to Mr. Hamburger's question is yes. A similar condition sometimes arises when an amplifier warms up. The abnormally high impedance of the valves during heating upsets the stability conditions and the oscillation then ensuing again upsets them further so that oscillations continue.

Mr. Wheeler will find references to the effect of feed-back on the input impedance of the amplifier in the published paper. His application is very interesting. Presumably the circuit referred to was not a cathode follower but a conventional valve amplifier with current feed-back in the cathode circuit. This, of course, increases the output impedance as well as the input impedance. The voltage gain in very nearly equal to the load impedance divided by the cathode resistance, and assuming the former to be 1,000 ohms this would give an amplification of 1/20,000. The resulting line voltage would thus seem to be too small to deal with usefully. Perhaps Mr. Wheeler would furnish the author with some further details.

Mr. Cox is, of course, right. Feed-back can be used in oscillator design to improve frequency stability. The principles of design are essentially the same as those applied to an amplifier.

The author has read Dr. Partridge's analysis of an output transformer with interest. It is unfortunate that the phase shift round on audio frequency transformer makes it somewhat difficult to include input and output transformers in the $\mu\beta$ chain as some of the advantages of the feed-back amplifier are otherwise lost in the coupling transformers. Thus to take a simple example, suppose an amplifier of 1,000 ohms output impedance be coupled to a load of 1,000 ohms through a one-to-one transformer. If feed-back be applied at the plate of the last valve, i.e. to the primary of the transformer, the impedance may be brought down. We will take an extreme value and suppose the impedance to fall to one ohm. It is clear that the amplifier cannot look like one ohm when viewed through the transformer, since the D.C. resistance alone will be much higher than this. One might, of course, exchange the 1,000/1,000 transformer by one designed to work from one ohm. The shunt resistance of this transformer, however, at low frequencies would be of the order of a few ohms, and though this would not appreciably reduce the output it would greatly increase the harmonic distortion at these frequencies. Shunt capacity would have a similar effect at high frequencies. Thus only by a large and expensive output transformer would it be possible to realise much of the advantages of low impedance conferred by voltage feed-back.

BIRMINGHAM DISCUSSION

F. H. Alston (Associate Member) :

In radio receivers, negative feed-back is usually applied to the output stage. What effect should we expect when an amplifier is terminated in this way by a moving-coil loudspeaker which has widely diverse variations of voltage phase angle depending on frequency ? Since it would appear that a given feed-back voltage 180° out of phase would have a greater effect than a similar voltage of, say, 135°, would it be reasonable to assume that in this case the frequency response characteristic would be affected ?

Would the feeding back of an out of phase voltage to the grid of the output valve cause any noticeable distortion of waveform, particularly in view of the fact that, by repeated passage through the amplifier and feed-back circuit of a proportion of the same signal, the phase angle would be slightly but progressively changed ?

Some commercial radio receivers using negative feed-back have a dull, lifeless tone similar to the effect produced by a heavily draped studio. If the amount of feed-back is reduced by alteration of the potential dividing circuit, the tone is more brilliant and pleasing. Is this improvement due to the minimising of a form of distortion caused by the feed-back principle, or merely to the reduced damping of the loud-speaker by the feed-back circuit ?

C. Stokes (Visitor) :

In a three-stage A.F. amplifier, is it better to apply negative feed-back to each stage separately, or to the amplifier as a unit ?

J. Cotterell (Associate) :

Can negative feed-back be effectively applied to valves operated under Class A, B and C conditions?

T. A. Waite (Visitor) :

Regarding the last question (applying feed-back to Class A. B and C amplifier) I do not think that the application of negative feed-back to Class C amplifier is of any value, since Class C amplifier is a non-linear amplifier designed for high efficiency, i.e. a high ratio of D.C. input to A.C. output, and the application of negative feed-back would reduce the efficiency and improve the linearity.

May I also ask Mr. Hill what is the effect of negative feed-back on the transient performance of an amplifier ?

The Chairman :

Although the perfect amplifier has almost been obtained, he would like to know whether the author was quite happy about the transient response. There had been a good deal of discussion about transformer coupling and other methods of coupling whereby transients could be handled in the best way, but could the author say if there was likely to be any advantage in the case of a feed-back amplifier with respect to transients ? Some work had been done on amplifiers with rising characteristics which gave good results on pure A.C. input but contained tuned circuits which were impulsed by transients. Was there any possibility of a similar occurrence with negative feed-back amplifiers ?

Mr. Bishop (Visitor) :

Asked what was the effect of feed-back on the amplitude characteristics of an amplifier. If he designed an amplifier and overloaded the valves could the distortion so created be eliminated by the use of negative feed-back ?

REPLY TO BIRMINGHAM DISCUSSION

Mr. S. Hill :

In reply to Mr. Alston, the effect of a phase shift in the amplifier, i.e. in the μ path, may be seen by writing the gain $\frac{\mu}{1+\mu\beta}$ and supposing μ to be a complex operator $\mu_1 + j\mu_2$. Thus, if $\frac{\mu_2}{\mu_1} = \frac{1}{\sqrt{3}} = \tan 30°$, the phase shift through the amplifier is + 30°. For $\mu\beta$ large, the value of the μ tends to insignificance, so that the amplitude characteristic is not affected. For $\mu\beta$ small, the expression may be rationalised into

$$\frac{\mu_1(1+\mu_1\beta)+\mu_2{}^2\beta+j\left|\mu_2(1+\mu_1\beta)-\mu_1\mu_2\beta\right|}{(1+\mu_1\beta)^2+\mu_2{}^2\beta^2}\ .$$

A plot of this expression against frequencies gives the overall gain in magnitude and phase, β being here taken as a real. In general the result will be seen to be a characteristic which is more nearly uniform with frequency in both magnitude and phase than if there were no feed-back. Provided stability conditions are met, one need not consider a phase shift through the amplifier as being progressively modified, i.e. the phase shift does not 'chase its own tail,' a balanced condition being automatically arrived at substantially instantaneously.

The effect of feed-back on tone is due to the increased loudspeaker damping. If one is used to a slight ringing, the tone may appear dead.

Mr. Stokes may care to note that in general it is better to apply feed-back to the amplifier as a unit. If applied to an individual stage, the previous valve is called upon to deliver more power, which may cause distortion. Moreover, with a single stage of feed-back it is not so easy to achieve the condition $\mu\beta$ large compared with unity which is desirable if the performance is to be substantially independent of the valves.

Replying to Mr. Cotterell, Mr. Waite and to a question touched on by the Chairman, I would point out that feed-back can certainly be applied to Class A, B and C amplifiers, but one has to remember that feed-back is not a kind of medicinal tonic which can be relied on to improve any amplifier to which it is applied. One has to ask what characteristics of an amplifier one wishes to modify, and whether feed-back will help or not depends on the individual case. One would not apply it to a harmonic generator where harmonic production is a desirable feature. The class C amplifier mentioned by Mr. Waite seems to be a similar case. On the other hand, if constancy of operation with varying external conditions is of prime importance one might use some feed-back at the expense of some of the desirable non-linearity.

Feed-back in general improves the transient response by the same mechanism whereby the steady state response is improved. Thus the application of a square-topped wave to an amplifier is an accepted indication of its transient response. Such a wave may be analysed by Fourier analysis into a series of steady sinusoids. The effect of feed-back is to make these sinusoids at the output a closer copy both in magnitude and phase of the same sinusoids at the input. Of course, one has to study the transient response of the feed-back path. If this is bad, the overall transient response may be worsened.

By amplitude characteristic Mr. Bishop probably refers to amplitude distortion. The author has used the words rather differently to refer to the change in the amplitude of the output with frequency as opposed to change of phase with frequency. Reduction in amplitude distortion is one of the main advantages of feed-back. Nevertheless, one must bear in mind the steepness of the amplitude curve for distortions over 5 per cent. A valve may give 10 watts at 1 per cent. and 20 at 5 per cent. distortion. By applying enough feed-back to reduce the 5 per cent. to 1 per cent. the output of the amplifier can clearly be doubled. It does not follow, however, that one could now draw 40 watts from the feed-back amplifier and get 5 per cent. distortion :

it might be 80 per cent. If the amplifier be rated at 1 per cent. tolerable distortion, we see that feed-back has doubled the output ; if it be rated at 10 per cent. the output may only go up by a negligible fraction of a watt.

The author was very cordially thanked for his paper at the conclusion of both meetings.

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FORTHCOMING MEETINGS

London and Home Counties Section, 1943/44

All meetings will be held at
The Institution of Structural Engineers,
11 Upper Belgrave Street, London, S.W.1

(*The following dates have been confirmed but in some cases differ from the provisional dates previously published. All meetings commence at* 6.30 *p.m.*)

October 28th, 1943 :

" Colour and Stereoscopic Television."
A Paper by John L. Baird.

November 25th, 1943 :

† " Stabilising Electronic Circuits."
A Paper by M. M. Levy (Associate Member).

December 15th, 1943 :

† " Selective Methods in Radio Reception."
A Paper by E. L. Gardiner, B.Sc.

January 27th, 1944 :

" Some Aspects of Special Electron Tubes "
A Paper by F. E. Lane (Associate Member).

February 24th, 1944 :

† A Review of Wide Band Frequency Modulation Technique."
A Paper by C. E. Tibbs (Associate Member).

March 30th, 1944 :

" Design for Quality Reproduction."
A discussion meeting which will open with an
Address by Dr. Malcolm Sargent.

April 27th, 1944 :

† " Modern Development of the Cathode Ray Tube,
with special reference to its manufacture and
testing."
A Paper by Hilary Moss, Ph.D.

† Preprints will be available three weeks before the meeting and *must* be applied for if required.

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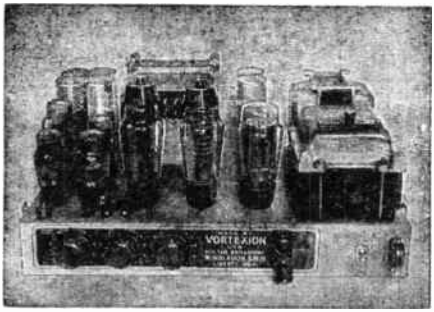

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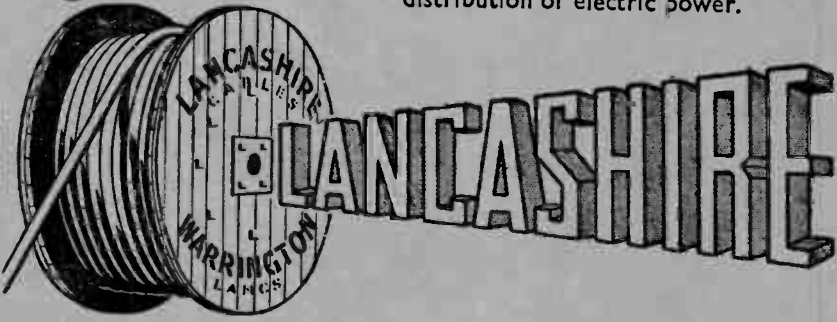

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The British Institution of Radio Engineers

Technical Papers

SOME NOTES ON THE PREPARATION OF MATERIAL FOR VERBAL PRESENTATION BEFORE THE INSTITUTION AND FOR PUBLICATION IN THE JOURNAL.

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TECHNICAL PAPERS.

THE dissemination of knowledge is one of the prime functions of the Institution. There are two ways in which this purpose is achieved: firstly, by the presentation of papers before meetings organised by the Institution; secondly, by the publication of papers and articles in the Institution *Journal.*

The first method brings members into intimate contact with the author of the work and makes possible the elucidation of obscure points and the discussion of side issues; but its scope, nevertheless, suffers certain limitations. The second method enables a far larger section of the profession to be reached, and the data set down remains permanently recorded for future reference.

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GENERAL CLASSIFICATION OF PAPERS

For the present purpose it is convenient to classify papers under two broad headings: (*a*) mathematical; and (*b*) non-mathematical. Those of the former type demand careful study, time for reflection, and possibly the facility for referring to other works. It is, therefore, considered that mathematical and purely theoretical contributions are often most satisfactorily presented in the printed form. On the other hand, non-mathematical papers dealing with applied science usually demand less mental effort and specialised knowledge on the part of the recipient, and consequently possess a direct appeal to members of widely diverse interests and attainments. Such papers are therefore very suitable for verbal presentation as well as for publication in the *Journal.*

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Papers by Student writers for reading before the Students' Sections are especially welcomed. Senior members of the Institution are urged to encourage the junior members working under them to prepare papers for reading before the Students' Section and for publication in the Students' and Graduates' *Journal.*

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It is not desirable that papers should be read literally at a lecture. The lecturer should contrive to maintain the alert interest of the whole of his audience for the whole of the time. To do this, a more colloquial style might be employed than in the case of a written paper; the subject may be treated less formally, and mathematical proofs need not necessarily be pursued in full detail; complete treatment should be included in the paper when it is subsequently published in the *Journal.* Lantern slides and diagrams projected by means of an epidiascope may be used as freely as desired. The exhibition of rare, novel or experimental apparatus always promotes interest. In brief, the author should encourage, enliven and inspire his audience rather than subdue it by the profoundity of his own attainment.

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The written paper should be formal, concise and complete. A short introduction should be given indicating the subject to be treated and the manner in which the paper contributes to the existing knowledge of the subject. The main subject matter must be arranged in a connected and logical sequence and should be satisfactory from the literary aspect. The repetition of material to be found in standard works or in readily accessible publications is undesirable, but original statements must be fully supported by experimental or mathematical proofs. The reference value of a paper is greatly enhanced by the inclusion in a convenient form of new data and of relevant data collected from dispersed sources. In the latter case appropriate acknowledgments must be made. It is especially desirable that a bibliography should be appended in order to facilitate further study of the subject.

All papers should be accompanied by a summary or abstract of not more than two hundred words. Any notice distributed to the technical press to assist them in reporting the paper will be taken from this summary.

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The Editorial Committee appreciate that many members are in a position to impart knowledge of considerable interest, but possibly of insufficient scope to form the basis for a complete paper. Such members are encouraged to present short, concisely worded articles, which will be eligible for publication, providing they attain the required technical and literary standard. These may be grouped for oral discussion at a meeting.

SUBMISSION OF PAPERS AND ARTICLES

All matter for the consideration of the Editorial Committee must be addressed to the Secretary, and may be submitted at any time. Papers to be read, if selected, in the first half of the session (September, October, November, December and January) should be received before the 31st May, and those to be read in the second half (February, March, April and May) should be received before the 31st October.

Contributions are subsequently submitted to two or more competent referees, who report independently to the Committee. The referees are selected in the light of their known ability to pass judgment upon the matter in question and, if deemed desirable, they may be recognised technical authorities external to the Institution itself. Every contribution is accorded unbiased and sympathetic consideration, and constructive criticism, advice and assistance is freely given in those cases where the standard of the original contribution justifies such a course.

Delay may often be avoided if intending authors, before setting to work, will communicate with the Secretary of the Institution on points about which they may be doubtful.

All papers accepted by the Editorial Committee and subsequently approved by the Council for publication are eligible for premiums independently of their being read before a meeting.

The oral discussion following a lecture is usually reported with the publication of the paper in the *Journal*. Discussion is also encouraged in the case of written papers, and is followed in subsequent issues of the *Journal* by the publication of correspondence contributed in response to the footnote which is appended to every paper of this kind as it appears.

BRITISH INSTITUTION OF RADIO ENGINEERS

PRACTICAL ADVICE ON PREPARING THE PAPER

The following hints are those suggested by the Editorial Committee to assist the intending author in the preparation of his paper. They are conveniently listed for easy reference, and it will be mutually helpful if they are carefully observed.

(*a*) The use of the first person should be avoided, the writer of the paper being referred to as " The author."

(*b*) With the exception of mathematical symbols and formulae, which may be written by hand, the paper should preferably be typewritten (double spaced) on one side of the paper only, with a margin of one and a half inches. The pages should be numbered.

(*c*) An average paper contains eight thousand words, plus tables and diagrams. The maximum length normally acceptable is twelve thousand words.

(*d*) Diagrams may be clearly sketched in pencil or ink, and these and other illustrations should be on separate sheets detached from the text. The Institution has facilities for the preparation of final drawings for block making.

(*e*) Diagrams should be numbered in their correct sequence, and appropriate references to them should be included in the text.

(*f*) Any footnote or reference to other published works should be inserted in the text directly below the line to which it refers, between it and the following line. All references should be in the following form: *e.g.*, " *Journal of the Brit. I.R.E.*, 1938 Vol. 3, p. 993."

(*g*) Symbols, terms and definitions should be in accordance with (1) " British Standard Graphical Symbols " (B.S.I. Publication No. 108); (2) International Symbols and Abbreviations adopted by the International Electro-technical Commission; and (3) the " Glossary of Terms used in Radio Engineering."

(*h*) MSS. should be sent by registered post, and the author should keep a copy.

(*i*) Copy in its final form should arrive at least one month before date of lecture.

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(*a*) Address the people in the back row. If they hear distinctly, everybody will hear.

(*b*) Allow a speaking time of about one and a quarter hours. A brief discussion may follow the paper.

(*c*) Blackboards, a lantern and an epidiascope will be provided by the Institution by arrangement with the Secretary.

(*d*) Lantern slides should be of standard size (3¼" x 3¼"). Diagrams to be projected by the epidiascope should be firmly drawn in indian ink, on stout white paper, which should not exceed size 6" x 6".

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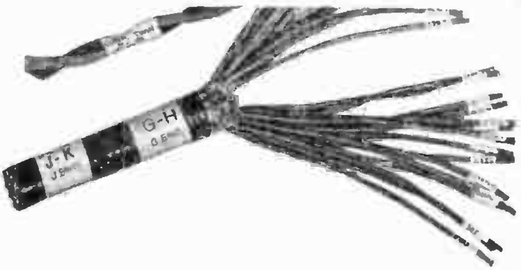

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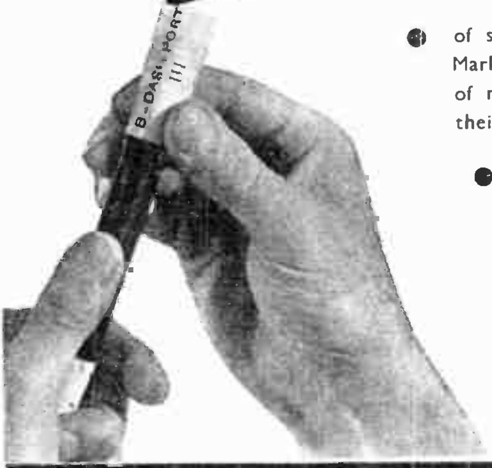

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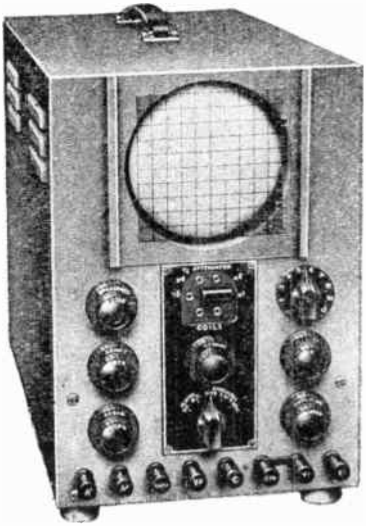

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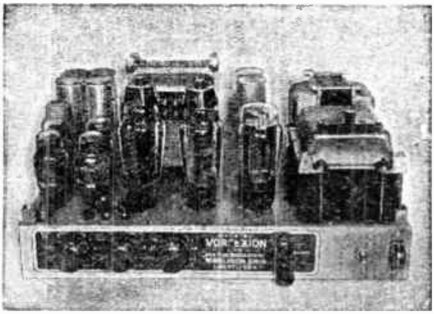

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INAUGURAL ADDRESS

by

SIR LOUIS STERLING
(President)

A paper read before the London Section of the Institution, at the Federation of British Industries, London, on September 25th, 1942.

Exactly two years ago, I addressed the Institution on the constructive work which can be done by learned societies, the importance of technical education and the service which can be rendered to industry as a whole by development of radio science. I therefore appreciate the honour of election to the highest office of the Institution and welcome the opportunity for personal contribution toward achieving the objects I have already outlined.

Post-war problems can be considered without in any way lessening our war effort, and I propose therefore to discuss the future of our profession with particular reference to post-war employment.

In common with aeronautical engineering, the development of radio and electronic science has been given impetus by the demands of war. This has thrown a responsibility on the radio and teaching professions, for with development the knowledge required of engineers has also expanded at an unprecedented rate. In this process of development there are possibilities for improving our national engineering educational system, for it must be remembered that technical training for our profession has been developed over a period of years in different localities and by various agencies—and often only in response to the immediate needs of groups of students with heterogeneous background and purpose. Opposition was often encountered from those trained in the older "practical" schools and imperfectly acquainted with the development of modern technique.

Such difficulties have been largely overcome by collaboration between the responsible Government Departments and the Radio Manufacturers Association ; specialised courses are now offered in our universities and technical schools, and at long last the industry has facilities for training those wishing to prepare for entry into the profession.

These war-time schemes must not be dropped ; we should adhere to the principle of training engineers, and, having trained them, ensure methods of registration. If registration is essential in war, it is equally necessary in peace, in order to ensure proper utilisation of man-power and as a means of checking overcrowding of an individual profession. This will not mean that any individual profession will become "closed," but, as I shall point out later, registration will assist in the control of training to ensure prospects of employment with a future.

The idea of peace-time registration of engineers is by no means new. A few years ago the late Professor W. Cramp, addressing the British Association, advocated the setting-up of a body with statutory powers to define the qualifications of persons entitled to call themselves " engineers." Then the aim was to prevent unskilled persons from jeopardising life and to check unprofessional conduct ; on this score alone registration is highly desirable, but it becomes even more desirable if also used for ensuring proper utilisation of man-power.

Registration of marine engineers by the possession of Board of Trade " tickets " has long been accepted, whilst strong reasons have been advanced for according similar recognition of the skill required of colliery electricians. The Dominions of Canada, South Africa and Australia have for many years now had forms of registration and qualification for certain types of engineers. Since engineering is now recognised as so much a part of any nation's life, and, in fact, international life, it is obviously of some importance to consider what standards of professional conduct (and ability) are required of its practitioners.

Registration, in fact, holds good with regard to installation engineers, and engineers in factories. They, or their assistants, may easily cause danger by faulty executions of good original design, and it would appear indeed that registration is desirable on the detailed and practical side of engineering as for those who prepare the original design. Certainly registration would increase the standard of competence, and so far as the British engineer is concerned, it is essential that in post-war years British products must be first-class and so help in securing increased sales both at home and abroad.

It may be argued that one of the main purposes of a " Law for the Registration of Engineers " is to institute standards of competence which should be regarded as minimum qualifications for those wishing to be termed " professional engineers." It may be suggested in return that responsible organisations in Government Departments would only engage competent men, but that does not necessarily follow.

For example, we have the many alterations and amendments made in the compilation of the war-time Central Register, because, although excellent in principle, the register did not at first take into consideration the specialist aspects of each and every profession—especially in the engineering industries. Consequently, there was an almost fatal tendency to generalise instead of specialise.

This was to a large extent quickly remedied, especially. I am pleased to say, by the three Services, by encouraging co-operation *from the professional engineering institutions*—the specialist bodies. The Brit.I.R.E. has given every assistance in this nationally important work and has proved by its help in the war effort and to industry that a definite status for radio and allied engineers is just as essential as for surveyors, architects and other members of older-established professions.

If registration is desirable, then should it be undertaken by one central Government department or by specialist bodies, such as our leading professional institutions ? Membership of a professional body not only necessitates educational and practical ability, but has the further advantage of entailing adherence to a professional code calling for a high standard of conduct. For those who devote their whole time to advising the public, there is the additional code of the Association of Consulting Engineers, more particularly with regard to independence of manufacturing and contracting interests.

In his Chairman's address to the Institution of Electrical Engineers at Manchester two or three years ago, Mr. J. W. Thomas expressed the opinion that legal certification with the object of protecting the title " Engineer " was not a live issue, and suggested that a recognised hall-mark of proficiency would come about in time through the general practice of those engaging engineers. That is probable, but it implies the need to educate the public *and* employers to appreciate the value of the qualified engineer. The organisation to do that was the Engineering Public Relations Committee, which is the product of collaboration between the major institutions, but this way will be longer and more arduous than the path of legislation. It is, moreover, a fact that the granting of Charters to old-established professional bodies has hastened the process of securing public recognition of the worth of professionally registered engineers. Government and public bodies invariably insist upon specialised professional qualifications when making appointments, and in this way encourage specialisation through registration or membership of the appropriate examining body.

The end of the war will doubtless see a boom in technical education corresponding to that of 1918-19. Educational authorities might well consider whether they give value for money and time in the sense that work accomplished should show a return. The trained student must be employed unless he is to be a handicap to the State, and the specialist professional institutions are best suited to act as the link between education and employment.

Many will, no doubt, consider it gross impertinence to talk of money in the same breath as education. The academic mind frequently affects a contempt for such sordid commercialism, with the consequence that students are allowed to complete their courses under the impression that in their degree or diploma they possess a first-class passport which will open all doors ; later they find that their training is, so to speak, merely a season ticket which, whilst perhaps admitting them to the platform, does not guarantee even standing room on the train.

Is the training received sufficiently practical? The suggestion that university and technical school students should spend periods in factories is a good one, but this co-operation between education and industry emphasises the desirable liaison functions of a professional body. Through its intimate collaboration with industry and its senior members the Brit.I.R.E. is able not only to afford liaison but particularly to direct personnel to those branches of the individual industry which will require personnel in the future. For example, television research may provide future employment for many thousands, whilst the scope for employment in sound transmission alone may be very restricted. Therefore it is of little use training only specialists in sound transmission. Teachers cannot, however, be expected to keep abreast of every future development, but expect and must have direction on the needs of industry.

Manufacturers, on the other hand, cannot be expected to undertake training of personnel other than providing facilities under the practical training scheme. This emphasises that the link between the educational system and employment must be the professional body which has for its objects :

(*a*) To encourage invention and research in all matters connected with its specialist branch of engineering. (Thereby creating future employment.)

(*b*) To hold meetings for encouraging professional intercourse and discussion of professional problems. (Thereby encouraging efficiency.)

(*c*) To co-operate with universities and all other educational authorities for the furtherance of education in radio science and engineering.

(*d*) To co-operate with industry in order to further the advancement of radio science to advance the professional status of the Institution and its members.

Registration by membership of the appropriate professional body is a further service of an Institution to the profession and members it represents. So far as the Brit.I.R.E. and the radio industry are concerned, we have reached the time when we can justify recognition from the State, education, and industry.

As our membership list is revised each year, it will be seen that the calibre of the Institution's membership increases. The Membership Committee is scrutinising with greater care than ever each application which comes before it. The Institution does not wish to restrict membership, it wishes to increase it—for in numbers there is strength—but the increase must be amongst those who are properly qualified and whose membership of the Institution will be beneficial to industry, to members and, of course, to the Institution.

The Brit.I.R.E., therefore, looks with confidence to the future. It sees ahead opportunities for development and progress which its founders could only have dreamed about, and if registration of engineers is adopted under the system I have suggested, then the Institution will be able to render even greater service to its members and industry, and thereby the State.

The

British Institution of Radio Engineers

ASPECTS OF MODULATION SYSTEMS

by

James Robinson, M.B.E., D.Sc., Ph.D., M.I.E.E., (*Member*).

A paper read before the London Section of the Institution, at the Federation of British Industries, London, on September 25th, 1942.

Radio Communication has introduced a most valuable art into civilisation, and one of the objects of Radio Engineers is to show how to employ it to the best advantage. It is of great importance to employ as many transmitters and receivers as possible, and the increase in the number of services brought into use in the last few years is most encouraging. Many technical difficulties have stood, and still stand, in the way of the utmost use of this new art, and it is the object of this paper to discuss one interesting feature, that of modulation of radio waves.

Various attempts have been made during the last 20 years to manipulate the art of modulation in order that as many services as possible can be employed, and to provide means whereby we can receive any desired service with the least possible interference from others, even though the services may employ frequencies which are very close together. A survey of the most important proposals should be of interest at the present time.

The fundamental principle which makes modulation necessary is that we cannot convey intelligence by radio means, or in fact any other means, on a single frequency. We normally have a carrier wave, which is a wave of a definite frequency and amplitude, but unless this is altered in some way it cannot convey an intelligent message. In varying this wave in any known way, we have, in effect, a number of other waves of different frequencies produced. Hence in order to convey intelligent signals we must visualise a wave band, and we must consider whether this hard fact puts a limit to the number of wireless services that we can employ simultaneously. It appears to mean that for each service we must have a definite wave band, which for broadcasting of sounds has been taken as 10 kc/s, and it has become customary to reserve such a wave band or channel for one single service. We apparently must not allow the channels to overlap, or else we shall have interference with our desired programme. The ultimate goal where we can employ the same carrier frequency, or alternatively the same channel, for more than one service thus seems to be an impossibility.

Various Methods for Increasing Communication Services

During the last 25 years this apparent restriction has been recognised more and more, and it has caused restless engineers to search for any possible method of escape, so that radio can continue to expand its applications and services. The chief aim of this discussion is to try to make clear how improvements can be effected by employing the modulation of the waves more and more intelligently, but before doing so it is of interest to note that other methods have been employed.

(1) After the last war, the International Authorities found it necessary to restrict the activities of amateur experimenters, as all medium and long waves were required for general purposes. They then forced amateurs to experiment with short waves, with a result which was very unexpected, for it was soon demonstrated that waves lower than 100m wavelength had very valuable properties for long-distance communication. This was a very interesting application of the old proverb that necessity is the mother of invention, and a very practical step was taken to extend the number of wave bands which were possible for communication. The search for other wave ranges is still continuing.

However, this is not the answer to the question as to whether we can use a single channel for more than one service.

(2) A very instructive step was to employ directional wireless ; thus we can concentrate transmissions into beams, and in this way we can save space in a geographical manner. So far, however, this has only been possible on short waves.

For all waves, long and short, improvements have been made by using directional reception. The G.P.O., on long waves, have employed receiving systems which receive only from a comparatively small angle of about 60°. This was a very definite step forward in providing some answer to the great problem.

(3) It has also been suggested that certain of the applications of wireless should be taken over by wires. This refers particularly to broadcasting, and we have seen one single wireless receiver employed to feed by wire many hundreds of homes. This was a distinct service, highly desirable, but there is a tendency to suggest an extension of this idea so as to accommodate broadcasting entirely on wires and to deprive the general public of one of its rights, the use of wireless for broadcasting. However, we must avoid political issues and merely point out that by adopting the system of wire instead of wireless broadcasting, we are merely admitting defeat, for there is a real outstanding problem of wireless to be overcome.

In addition to these methods, many attempts have been made to manipulate the art of modulation both at the transmitter and the receiver in order to attempt to find a satisfactory solution.

There are two principal methods of modulating carrier waves : those of amplitude and of frequency modulation. In the case of amplitude modulation, the frequency of the carrier waves is kept constant, and the amplitude is varied in accordance with the speech or vision or telegraphic signals which are to be transmitted. In the case of frequency modulation, the amplitude of the carrier waves is kept constant, but the frequency of the waves is varied in accordance with the signals to be transmitted. Both methods of modulation have many aspects, and it will be impossible for me to deal with them completely in this discourse. An attempt will be made to describe certain features of a more general character, in order to show how the different kinds of modulation can provide advantages in particular circumstances, in the hope that many engineers will be guided in their more detailed reading of the subject. The subject of frequency modulation has only comparatively recently become topical, but a number of writers have already dealt with it in this country. In particular, I would refer readers to Howe's[1] discussions in the *Wireless Engineer*; also to an excellent mathematical investigation by Keall[2]; and to the textbook by Ladner and Stoner, *Short Wave Wireless Communications.*

Amplitude Modulation

The better-known method of modulation is to vary the amplitude of the carrier waves. In its oldest form it merely consists of keying for telegraphic signals when the waves were either on or off. However, for telephony or television it is necessary to introduce refinements, and we have to consider partial, rather than complete, change of amplitude. Fig. 1 shows continuous waves (*a*) of a definite frequency and of a constant amplitude. It also shows the amplitude of these waves varied at (*b*) whilst retaining the same frequency.

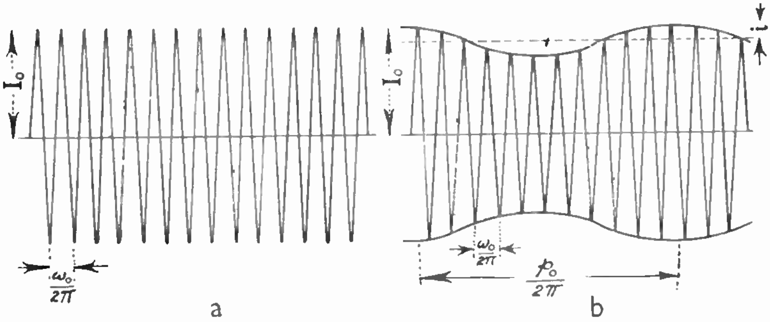


Fig. 1.—*Continuous waves of frequency* $\frac{\omega_0}{2\pi}$. *At* (a) *constant amplitude waves represented by* $I = I_0 \sin \omega_0 t$. *At* (b) *the same waves are shown amplitude modulated at frequency* $\frac{p_0}{2\pi}$, *represented by* $I = I_0\ (1 + m \cos p_0 t) \sin \omega_0 t$. *Heterodyne effects are qualitatively similar to amplitude modulation. A heterodyne of the form* $I = I_0 \sin \omega_0 t + 2\, i \sin (\omega_0 + \rho_0)t$ *has almost the same curve, except that* (*i*) *the envelope is somewhat distorted*; (*ii*) *the R.F. oscillations have not a constant frequency* $\frac{\omega_0}{2\pi}$, *although they vary about a mean frequency* $\frac{\omega_0}{2\pi}$. *Hence this is a phase modulation.*

The continuous waves are represented by $I = I_0 \sin \omega_0 t$ . . . . (1)

where $\frac{\omega_0}{2\pi}$ gives the frequency.

When these are modulated by another frequency $\frac{p_0}{2\pi}$ we really change the amplitude I_0 to superimpose on it a variation at frequency $\frac{p_0}{2\pi}$, and this is represented by:

$$I = I_0 \left(1 + m \cos p_0 t\right) . \sin \omega_0 t \quad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

These mathematical expressions immediately show that we have more frequencies present than $\frac{\omega}{2\pi}$ and $\frac{p_0}{2\pi}$, as the modulated waves become

$$I = I_0 \sin \omega_0 t + \frac{mI_0}{2} \sin \left(\omega_0 + p_0\right)t + \frac{mI_0}{2} \sin \left(\omega_0 - p_0\right)t \quad \ldots\ldots (3)$$

Hence the number of radio frequency waves are now three instead of the original single wave $\frac{\omega_0}{2\pi}$. We have introduced two other high frequency waves at frequency separation from the carrier of $\frac{p_0}{2\pi}$, these having equal amplitudes.

This mathematical expression does not only represent an abstract view, but physical fact. This can be verified if we actually employ a highly selective receiver to tune to each of the three waves in turn.

When many modulation frequencies are employed together, as in speech, etc., we obtain a pair of side frequencies for each modulation frequency, and then if the highest modulation frequency is $\frac{p_s}{2\pi}$ there is a high frequency wave band in all of width $\frac{2p_s}{2\pi}$.

It thus appears as though we must space radio services by twice the highest modulation frequency as in Fig. 2. If we bring them closer together, we shall have the side frequencies of one transmission overlapping into the waveband of another transmission.

About 15 to 20 years ago, the problem was still more complicated, for even if the services were kept at some considerable frequency separation, so that no overlap of side frequencies occurred, it was not easy to receive any service without interference from the other. This was particularly the case if one wished to receive a weak service when there were powerful transmissions on one or both sides of the desired channel. In fact, it was not easy to receive a single programme without hearing the other side programmes in the background.

This was a kind of interference which we can now call Programme Interference. It is not easy for engineers of to-day to cast their minds back to those days, but this is what was generally understood by interference at that time. The answer to it was to make the receiver more selective. However, for many years it was considered that increased selectivity did not give the desired solution, for it was considered to be a rose with many thorns, and that if we made the receiver too selective it would not reproduce all side frequencies faithfully (see Fig. 3). In fact, the selectivity could only be made high enough by removing the damping from the circuit, and then it was thought

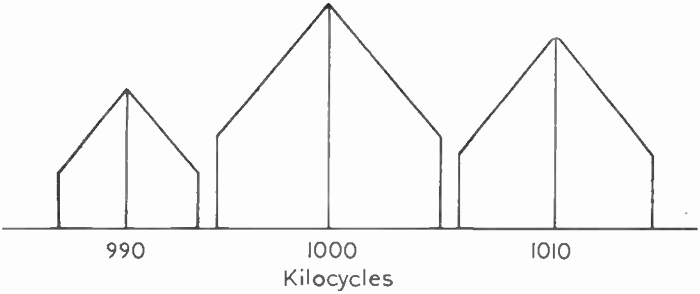
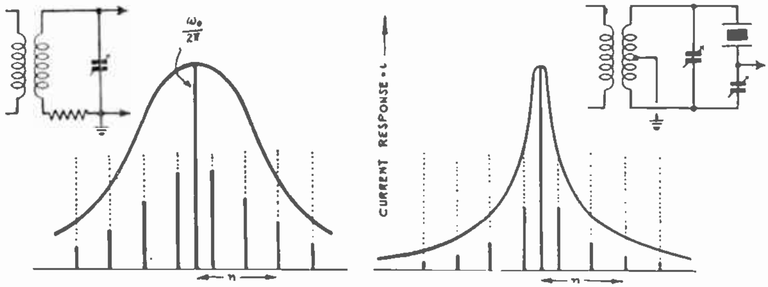


Fig. 2.—Graphical illustration showing the frequency separation necessary between normal adjacent communication channels.

that the original transmission could not be reproduced faithfully. Even for telegraphic signals, if the selectivity was too high the receiver would continue to vibrate in the dead spaces and thus high-speed signalling would be impossible. One of our best-known authorities, Professor G. W. O. Howe[3], generalised this by stating that a highly selective circuit would completely ignore very rapid alterations of the amplitude.

Thus one of the problems of radio communication was how to employ high selectivity to eliminate interference from neighbouring channels, and nevertheless be able to give faithful reproduction of the original transmission. Two different methods were employed, the first being the design of band-pass receivers which are now well known, although at that time they were exceedingly difficult to construct and maintain.



a

b

Fig. 3.—R.F. distortion by side band attenuation by selective circuits. In (a) *a high " Q " circuit ; in* (b) *a piezo-electric crystal circuit. For very high selectivity, each side of the resonance curve is practically a hyperbola. The vertical lines represent the side frequencies, the dotted portions showing the attenuation.*

The second method was the " Stenode," and its principles are now being widely employed, although even now the reasons for its efficiency are still insufficiently understood.

The Stenode

The Stenode method is to employ very highly selective circuits which will cut down the side frequencies progressively and, after rectification, to employ tone correction to restore the desired audio frequencies to their correct values. If very high selectivity is employed, I showed that the side frequencies are cut down by an amount proportional to the frequency separation from the carrier, and thus a very simple principle could be employed to correct the amplitude, this being to employ an audio frequency amplifier in which the degree of amplification is directly proportional to the frequency. In this way correct reproduction of the desired programme could be obtained.

This method removed interference from neighbouring channels of the type then recognised as the only or chief form of interference, *i.e.* Programme Interference. This was very obvious when demonstrated, but it was so unexpected that many engineers who did not witness the equipment in operation would not easily accept it. Some of them who did witness it thought that it contradicted the side-band theory, and thus it was assumed in some quarters that I must be using some properties hitherto undeveloped, such as frequency modulation. Actually, a property which had previously had very little recognition was involved, but it was not frequency modulation. To show how surprising this result was, I would recall that one of the well-known radio engineers of that time, P. P. Eckersley, wrote in *Popular Wireless* (Feb., 1930) as follows :

> " If we had an ultra-selective receiver . . . this receiver will not receive all the side bands, and we get only the bass notes.
>
> " It is no good in this connection saying that we will make the bass notes stronger in the high frequency spectrum but then amplify the high frequency and so level it up because, as a *reductio ad absurdum*, if the high frequency response curve is narrow enough, it would not get any high frequency side bands and you cannot amplify anything. If you do, in your high-frequency system, reduce the outer side bands to something very small, but make them strong again in a low-frequency system, the receiver response is just the same."

This actual quotation shows that in Eckersley's opinion no advance could be made by employing very high selectivity. He was not alone in this view at that time. He and many others had completely misunderstood what was happening. A very important fact has been overlooked by them, which is : " That in addition to the two processes of attenuation and restoration, there is the irreversible process of Rectification."

In a lecture to the Radio Club of America[1] in 1930, I pointed out the importance of the rectifier in the Stenode and referred to the fact that if two carrier waves, which are both modulated, arrive at a rectifier together, the stronger carrier will actually prevent the modulation of the weaker carrier from being efficiently received. In fact, the strong carrier actually demodulates the weaker carrier. A function of high selectivity in the Stenode is to make the desired carrier much stronger than an interfering carrier of a slightly different frequency, and thus the desired strong carrier prevents the weak interfering programme from being efficiently rectified. This effect is so pronounced that, in the Stenode, the interfering programme is practically non-existent, even when the channels are very close together.

The word " demodulation " was introduced to describe this effect, and it seemed to be a satisfactory term, but, unfortunately, the same word has come to be used for a more widely known phenomenon, that of rectification itself, and thus it is advisable to introduce another term. In this discussion I shall refer to it as Interfering Programme Demodulation.

Although the Stenode initiated much discussion of this rectifier effect, and some valuable investigations were made which established the behaviour of a rectifier in removing interference from a weak carrier, this " Interfering Programme Demodulation " is still unknown to, or not understood by, many engineers. In view of its efficiency, of its importance in high selectivity, and of the fact that Armstrong employs it in his frequency modulation system, an attempt will be made to make it easier to understand by an average engineer.

Effect of the Rectifier on Interference

When a single modulated wave arrives at a rectifier of the form as given by equation 3, we have three different waves present simultaneously ; the carrier wave w_0t of high amplitude, with two other waves or side frequencies $\frac{1}{2\pi}\left(\omega_0+p_0\right)$ and $\frac{1}{2\pi}\left(\omega_0-p_0\right)$. Each one of these waves is of far too high a frequency to be heard by the ear, and, in fact, we are not concerned so much with their actual frequencies as with the difference of their frequencies, which is $\frac{p_0}{2\pi}$, the actual modulation frequency.

Equation 3 can be rewritten as :

$$I = I_0 \sin \omega_0 t + i_0 \sin \left(\omega_0 + p_0\right)t + i_0 \sin \left(\omega_0 - p_0\right)t \; . \; . \; . \; . \; . \; . \; . \; . \; (4)$$

With a square-law rectifier, the modulation output is obtained from the product of the carrier I_0 with each of the side frequencies, and these two products can be written as :

$$i_0 I \; \sin \omega_0 t \; . \; \sin \left(\omega_0 + p_0\right)t + i_0 I \; \sin \omega_0 t \; . \; \sin \left(\omega_0 - p_0\right)t \; . \; . \; . \; . \; . \; . \; (5)$$

The acoustical output is therefore $2\, i_0 I \; \cos p_0 t$.

Thus the acoustical output depends on the amplitude of the carrier I_0 and also of the side frequency i_0. The influence of selectivity on the modulation output is thus apparent, for if we tune the receiver to the carrier wave I_0, this carrier has its amplitude at maximum, whilst the side frequencies i_0 have their amplitude reduced somewhat according to the resonance curve.

On the other hand, when the receiver is out of tune, both the carrier and side frequencies have their amplitudes reduced considerably as at $I_0^1 i_0^1$. The modulated output in this case is $2\, i_0^1 I_0^1 \cos p_0 t$, which is the product of two terms, both of which have had their amplitude reduced. When in tune, the modulated output is $2\, i_0 I_0$ and as only one of these terms has had its amplitude reduced, it is obvious why a selective receiver enables us to obtain the maximum output by tuning accurately.

When we have two similarly modulated waves present simultaneously of different frequencies as in Fig. 4, it is thus obvious why the modulation output of the waves which are in tune is much stronger than that of the waves which are out of tune.

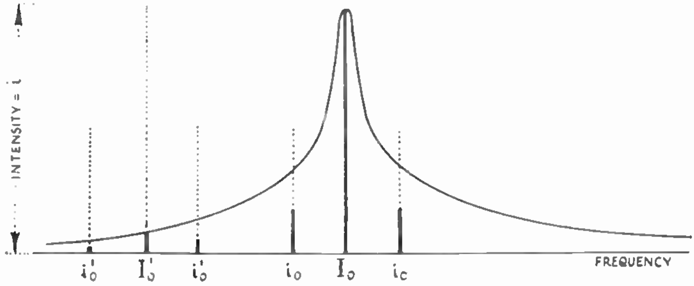


Fig. 4.—Square-law rectifier output. The curve represents the selectivity of the receiver, peaked at the desired service at I_0. The output is proportional to the product of the amplitudes of the carrier and side frequencies. Selectivity decreases the effect of an interfering programme $I^1{}_0$, whose output is approximately $2\, I^1{}_0 i_0$.

Thus here we have one reason why, with very high selectivity, we can cut down the interference from a neighbouring channel. When we later employ tone correction, it will not restore this interference as was expected by Eckersley and others, because the frequency of the modulation for both desired and unwanted services has been assumed to be the same in Fig. 4.

For linear rectification, the modulation output depends only on the amplitude of the side frequencies, and thus again it is seen that the interfering programme is cut down. Whilst this effect alone gives us one cause for the benefit of high selectivity, this is not the chief effect of Interfering Programme Demodulation, which is even more beneficial.

Interfering Programme Demodulation

This is a rectification effect, quite apart from any considerations of selectivity. Thus, if we have a receiver which is equally responsive for all frequencies, and if we have a modulated service B (Fig. 5), with its two side frequencies bb received simultaneously, as shown in Fig. 5, with a pure carrier A which is separated from B by a frequency which we shall, for the moment, consider to be supersonic, we shall find that, with a linear rectification, the modulation output of B depends on the amplitude of the carrier A. As the amplitude of A is increased, the modulation output of B actually diminishes.

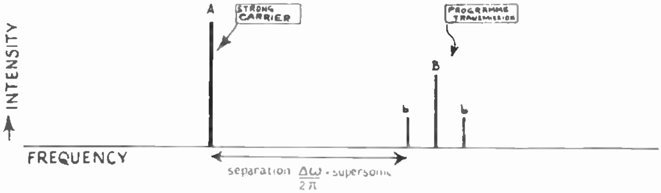


Fig. 5.—Interfering programme demodulation. With a linear rectifier, the output from Bb is reduced by the presence of A to a fraction $\frac{1}{2}\frac{B}{A}$ *of its original value.*

This fact was first discovered by Beattie[5] and has been experimentally verified by Butterworth, Appleton and Armstrong.

In order to obtain a physical reason for this effect, let A have frequency n_0 and B that of $(n_0 + q)$, where q is greater than 5,000 cycles, so as to be inaudible. If B is unmodulated we shall obtain a resultant effect of the two waves as shown in Fig. 6c, which is the form of an ordinary heterodyne effect with the beats of frequency q.

When we allow B to be modulated at a frequency f we obtain a resultant effect as in Fig. 6e. In this case the heterodyne beats are not of constant amplitude but actually vary in amplitude at a frequency f.

This is very instructive, for it is immediately seen that the beats of frequency q actually appear to be modulated at a frequency f.

When we rectify the complex wave, we eliminate the lower half of Fig. 6e and we are left with the top half, which still appears to need further rectification if we are to receive the modulation frequency f. We appear to have a new carrier frequency q modulated at frequency f, and as we have already applied rectification, there seems no reason why we should receive the tone of frequency f at all, particularly if the rectification was linear. In fact, the Interfering Programme of frequency f is suppressed, or almost completely suppressed, because of the presence at the rectifier of waves of different frequency but higher amplitude. This is the Interfering Programme Demodulation. However, if the mean value of envelope yy_1 is elevated above the zero response line xx_1, we shall have some small response of the modulation F when the rectification is square law.

This physical resoning should make it clear why the demodulation of a weak carrier by a strong carrier occurs. Actually, the amount of demodulation of the weak service increases progressively as the strong carrier increases. Measurements were given by Butterworth, Appleton and Armstrong. Appleton's results show that : " If strong and weak signals of carrier wave intensities A and B respectively are simultaneously received with a linear detector the modulation of the weak signal is reduced to a fraction $\frac{1}{2}\frac{B}{A}$ of its original value." There is also some influence on the strong signal, but this is very small, and actually the modulation of the strong signal is reduced slightly, to $1 - \left(\frac{B}{A}\right)^2$ of its original value.

The mathematical theory of demodulation has been investigated by Butterworth,[6] Moullin,[7] Appleton,[8] Colebrook,[9] Aiken.[10] Appleton's method is given in Appendix 2.

It was originally thought that this demodulation would only occur when the frequency separation between the two carrier waves was supersonic, but later investigation showed that it occurred for other frequency separations.[9]

Interfering Programme Demodulation and the Stenode

This principle of the demodulation of a weak carrier by a strong carrier is of very great importance, and its application has already made itself apparent in the Stenode and in Armstrong's system of frequency modulation. We shall return to Armstrong's application later, but at present we shall discuss the importance of this phenomenon as applied in the Stenode.

It still appears to be a mystery to many engineers why the Stenode does eliminate some type of interference so efficiently, and one reason undoubtedly is that this principle of Interfering Programme Demodulation has so far not been appreciated by these engineers. A strong carrier has this important effect : that it will cut down the modulation on the neighbouring channel to practical extinction, provided we can make our own carrier strong compared with neighbouring carriers. Hence selectivity has a very important part to play in wireless reception as it gives us the certain means for increasing the amplitude of the desired carrier in comparison with the interfering carrier. In fact, there is no limit to the selectivity we can employ, and the greater the selectivity the more efficiently do we cut down the interfering carrier, and thus its disturbing effect. I have constantly advocated that we should employ the utmost selectivity and introduce the most selective device known, the Quartz Crystal, for this purpose. With a quartz crystal, it is quite easy to cut down the interfering carrier on a neighbouring channel 10,000 times (80dB) or more, and thus it becomes possible to receive a weak service even when it has two powerful services on the neighbouring channels. Even when the interfering service is closer than 10 kc/s its modulation can be eliminated when the selectivity is high.

The Stenode thus contributed to the solution of the outstanding problem of attempting to eliminate all interference and thus to increase the number of available channels of communication. It eliminated the programme interference so efficiently that it appeared to challenge the accepted mathematical theory of modulation. In fact, it appeared to many as if selectivity has actually removed interference altogether, for it is to be remembered that in those days, most engineers considered programme interference as the only type of interference.

However, the Stenode was so efficient that it removed a stumbling block to progress—the programme interference—thus allowing other forms of interference to show themselves. These other forms of interference can be classed generally as heterodyne effects. Of course, the heterodyne whistle was known before the Stenode was introduced, but there were other types of heterodyne which were known theoretically to certain mathematicians and which probably had very seldom been observed. I am referring to so-called "side-band splash," which is really a form of heterodyne effect.

The heterodyne whistle is an effect produced by the inter-action of a single interfering carrier wave with the desired carrier wave. This produces a beat frequency as shown in Fig. 6c, and if this is in the audible range it appears as a whistle. Splash is a similar effect where the interfering wave happens to be a side band of a neighbouring channel, which side band happens to fall into the resonance curve of the receiver. As the side bands are not usually continuous, we do not obtain a continuous whistle, but an effect which is described aptly by the word "splash." Referring to Fig. 4, if we assume that the interfering programme I_0^1 is within 5,000 cycles of the desired carrier, we obtain a whistle between the carriers I_0 and I_0^1. If the side bands i_0^1 are continuous, we shall also have whistles between both of them and the desired

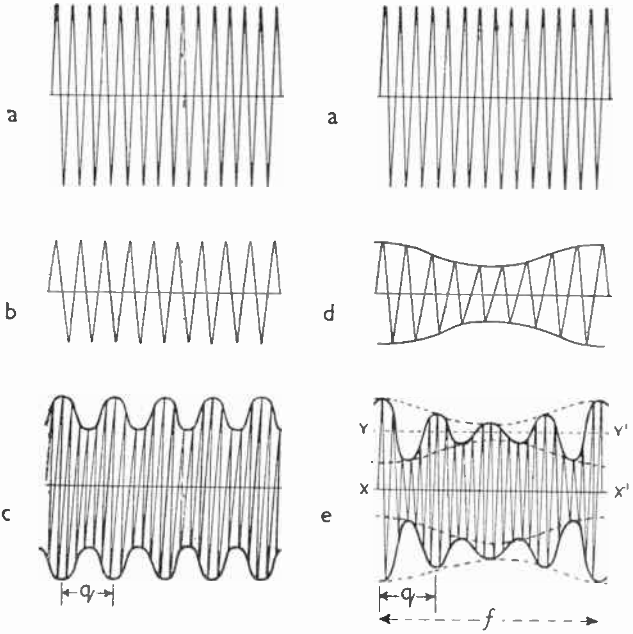


Fig. 6.—Interfering programme demodulation. Unmodulated waves of frequency n_0 from service A are shown at (a) ; *those from service B, of frequency $n_0 + q$, are shown unmodulated at* (b). *The resulting heterodyne effect, with beats of frequency q, is shown at* (c). *At* (d) *carrier* (b) *is modulated at frequency f resulting in the complex pattern* (e). *The heterodyne q is now modulated at frequency f.*

carrier I_0. When the side bands i_0^1 are variable, both as regards amplitude and frequency, this heterodyne effect becomes of the nature of splash.

We may also have another disturbing effect between the interfering side bands and the desired side bands, but this is so small as to be usually negligible. It is thus seen that inherently the Stenode does not eliminate such heterodyne effects, as these depend both on the interfering wave and the desired carrier. It does eliminate effects which depend on the interaction of interfering waves amongst each other.

Other disturbing effects which occur in receivers are amplifier noises, local noises and atmospherics. Generally, we have a background noise which can be regarded as a series of disturbing waves spread over very wide wave bands. Any one of these disturbing waves can be looked on similarly as a disturbing heterodyne wave.

Hence the use of high selectivity showed that we can eliminate certain forms of interference, but we are left with those disturbances which originate from waves, inside the desired wave band, which cause interaction with the desired carrier wave and produce heterodyne disturbance of the general kind.

Single Side Band Communication

The narrowing down of the received wave band thus appeared to be a highly desirable step, and a decided advance was made by operating only on one side band instead of on both side bands. In this way we can halve the general interference and also make it possible to accommodate twice as many services. It is unnecessary to discuss in detail why it is possible to employ a single side band, but merely to refer to the equation 3, which gives the expression for a carrier wave $\frac{\omega_0}{2\pi}$ modulated by a single modulating frequency $\frac{p_0}{2\pi}$. This gives us a carrier and a side frequency on both sides of the carrier. If we delete the lower frequency represented by $\frac{1}{2\pi}\left(\omega_0 - p_0\right)t$ we still have sufficient waves left to give us, on rectification, the desired modulation frequency. Hence it appears to be quite sufficient to transmit only one side band. Of course, the carrier frequency is necessary in order to obtain the correct relative modulation frequency at a rectifier.

The single side band can be obtained at a transmitter by first producing normal modulation and then, by means of a selective circuit, eliminating one of the side bands. Apart from the advantages given by saving space in the ether and cutting down interference, there is a further advantage, which is that power can be saved in the output stages of the transmitter. Thus, for 100 per cent. modulation with both side bands, we need 50 per cent. for the carrier alone, and the other 50 per cent. is divided between the two side bands. Hence by deleting one of the side bands, we save an appreciable amount of power. A further step has been taken to eliminate the carrier at the transmitter so that the full power can be concentrated on the single side band. With this method it is necessary to replace the carrier at the receiver, and this involves such a skilled operation that it has so far only been possible on communication services. It is necessary to use a local oscillator and to maintain its frequency identical with that of the carrier which was deleted at the transmitter. A practical receiver for single side band transmission is an outstanding necessity because of the advantages of power saving and of overcoming interference.

The quartz crystal gate, which I introduced at the same time as the Stenode, should help this single side band technique. It is quite easy to employ a quartz crystal receiver to give single side band reception, and I have often proposed that single side band transmission should be effected by transmitting a small portion of the carrier, when by using a quartz crystal receiver and tuning to the carrier, we have the true carrier actually enhanced by the crystal.

Stenode Transmission

A very simple method to obtain the benefits of selectivity is to employ a very highly selective receiver such as a quartz crystal. This will distort normal transmission so that low notes will be much stronger than high notes. The Stenode receiver actually corrects this distortion in the low-frequency circuits of the receiver. However, it is quite possible to apply the correction at the transmitter so that we transmit the modulation after it has been put through an amplifier which amplifies the audio frequencies in a manner such that the amplification is directly proportional to the frequency. Then at the receiver we merely need to employ a very selective device with normal amplification both at radio and audio frequencies.

If we postulate quartz crystal receivers, then again we can make the transmitter much more efficient, as we need only transmit a low percentage of the carrier so that most of the power can be used for the side bands. Again, we can make this transmission of the single side band type as it is very easy to employ a quartz crystal receiver to act as a single side band receiver. Thus we obtain further gains in efficiency at the transmitter and a saving in space in the ether.

The fact that we can concentrate most of the power at the transmitter into a single side band means that we can at the receiver obtain a considerable improvement in the signal to noise ratio. By restricting the wave band, we cut the disturbance down at once by 50 per cent. In addition, we require to transmit only a small value of the carrier, thus increasing the power in the side band, so that over all we shall increase the signal to noise voltage ratio by a factor of not less than three.

The gains will in all probability be greater than this, for an entirely different reason. The acoustical spectrum covers a band from about 30 to 10,000 c/s, but in general most of the energy is involved in the production of the lower frequencies from 100 to 500 c/s. Thus normally the voltage level is very much higher for the low frequencies than for the highest frequencies. When we transform the acoustical spectrum by putting it through an amplifier whose amplification factor is proportional to the frequency, we shall increase the voltage in the higher frequencies. In order that the power in the side band shall not be altered, this will mean that we must transmit the lower frequencies at somewhat lower voltage level. However, owing to the normal preponderance of the energy in lower frequencies, we should find that the upper frequencies have a considerable voltage gain whilst the lower frequencies are comparatively little diminished.

Thus, in all, this single side band Stenode transmission system should enable us to improve the signal to noise voltage ratio by a factor of 5 or 6.

These noises are spread over the wave band, and thus when we employ a very selective receiver such as a quartz crystal these noises will be cut down according to where they appear on the resonance curve.

Frequency Modulation

Whilst all this work which has just been described was proceeding in attempts to remove interference of all kinds from wireless communication, the possibilities of frequency modulation were frequently being referred to. This form of modulation was suggested in very early days of Wireless and referred to in the well-known text books of Eccles and Zenneck. It has also been used in continuous wave telegraphy for many years, where keying is performed by changing the frequency. There was a considerable air of mystery about it, as very few engineers had any idea of its theory or of how it could be carried into practice, but on many sides there were hopes that sooner or later it might be shown to be practical and useful. The air of mystery was exemplified at the time the Stenode was introduced, for few engineers could understand why such good results could be obtained with the Stenode when the side band theory appeared to deny them, and some engineers actually suggested that the Stenode must be employing frequency modulation in some form.

Actually, before developing the Stenode, I had thought round the subject of frequency modulation in the hope that we might be able to make some advance in the art of communication if we could employ frequency modulation with very small variations of the carrier frequency, and actually I had thought that we might use the Quartz Crystal,[11] to produce these narrow frequency deviations and also to convert the frequency variations at the receiver back to amplitude variations. The method for very small deviations is to employ a quartz crystal to control the frequency of an oscillating circuit. The frequency of the quartz crystal depends to a small extent on the air gap between the crystal and its holder. One of the plates of the holder is employed as the diaphragm of a microphone, and thus the air gap is varied in accordance with the oscillatory current in the microphone, and hence the frequency is changed periodically by a very small amount. The preliminary idea seemed hopeful, as we should only be employing very narrow frequency deviations, probably less than 50 c/s., and we could detect these by a very highly selective device such as a quartz crystal.

The whole idea of frequency modulation is attractive, as it appears to give a means for transmitting signals which is quite distinct from the natural disturbances which are encountered in wireless communication. These disturbances all produce amplitude changes in the receiving equipment, whilst a frequency modulation system was intended to change the frequency of the waves without producing any amplitude change. Hence, it was considered that it would be possible to eliminate the effect of the disturbances by employing means such as limiting or opposed systems of detection.

My own experience in thinking out the possibilities of frequency modulation are probably typical, because I very soon discovered two stumbling blocks, first that frequency modulation must produce side frequencies and, in fact, that it produces a very complicated series of such as distinct from the simple case of amplitude modulation where the side frequencies are of a very simple nature ; and second, that disturbances such as heterodynes produce not merely amplitude variations in the receiving circuits, but also actual phase and frequency changes. These two facts certainly acted as a deterrent. As will be seen below, the side frequencies associated with a modulation frequency $\frac{p_0}{2\pi}$ consist only of a simple pair $\frac{1}{2\pi}\left(\omega_0 \pm p_0\right)$ in the case of amplitude modulation, but in the case of frequency modulation we have many pairs of side frequencies :

$$\frac{1}{2\pi}\left(\omega_0 \pm p_0\right),\ \frac{1}{2\pi}\left(\omega_0 \pm 2p_0\right),\ \frac{1}{2\pi}\left(\omega_0 \pm 3p_0\right) \ldots\ldots\ldots\ldots \quad (1)$$

and so on, and further the amplitudes of these various side frequencies do not follow any simple law. Again, if a heterodyne produces phase or frequency variations of the desired carrier in addition to amplitude variations, then we have lost the actual thing we were searching for, i.e. a means for distinguishing between the desired and the interfering waves.

The whole problem of frequency modulation thus appeared exceedingly difficult, and theory seemed to show that distortion of desired signals would be very great and that there seemed to be little hope that interfering effects would be removed. Theoretical investigations were made by Carson[12] and Van der Pol,[13] and, indeed, Carson deduced from his analysis that the distortion would be so great that there seemed little hope of success.

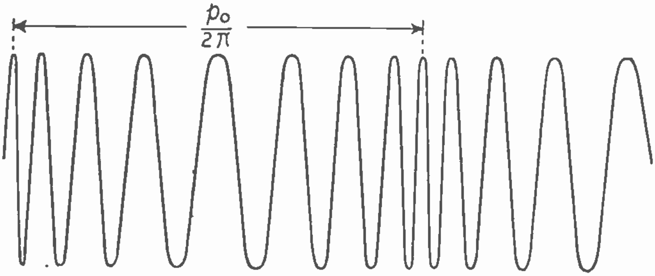


Fig. 7.—Frequency modulated waves represented by $I = I_0 \sin(\omega_0 t + m_f \sin p_0 t)$. *The actual change of frequency (deviation) is determined by the modulation amplitude* m_f. *The rate of deviation is determined by the modulation frequency* $\frac{p_0}{2\pi}$.

Let us examine the subject in a little detail. Amplitude modulated waves (A.M.) are represented by:

$$I_0 = I_0 \sin \omega_0 t \left(1 + m \cos p_0 t\right) \ldots\ldots\ldots\ldots \quad (2)$$

which can be written as

$$I_0 = I_0 \sin \omega_0 t + \frac{mI_0}{2} \sin\left(\omega_0 + p_0\right)t + \frac{mI_0}{2} \sin\left(\omega_0 - p_0\right)t \ \ldots \quad (3)$$

The form of the oscillation is shown in Fig. 1b. Expression 3 shows we can represent the modulated waves as the simultaneous presence of three distinct continuous waves.

There is a definite phase relationship between these three waves, and this can be expressed simply by stating that the resultant of the two side frequencies is always in phase with the carrier frequency or opposite to it. The two side frequencies together give us $mI_0 \sin \omega_0 t \cos p_0 t$.

This is a comparatively simple relationship, for there are only two side frequencies, and their amplitudes are equal.

Frequency modulation, on the other hand, has the frequency of the carrier changed by an amount which depends on the amplitude of the modulation, and this frequency change occurs at a number of times per second which corresponds to the modulation frequency. Thus, if the carrier frequency is 1,000,000 c/s and we have a modulation frequency of 1,000 c/s, then a weak modulation will bring the carrier frequency from 1,000,000 to 1,000,010 back to 1,000.000 and then to 999,990 and back to 1,000,000, this process occurring at the rate of 1,000 times per second. The change of frequency of the carrier is in this case for a weak signal only, 10 c/s, and this is called the deviation or excursion. A strong modulation of the same frequency will merely change the deviation to 500 c/s, or even to 10,000 c/s or more.

We can represent frequency modulated waves by

$$I = I_0 \sin\left(\omega_0 t + m_f \sin p_0 t\right) \ldots\ldots\ldots\ldots\ldots\ldots (4)$$

This can be written as

$$I = I_0 \cos\left(m_f \sin p_0 t\right) \sin \omega_0 t + I_0 \sin\left(m_f \sin p_0 t\right) \cos \omega_0 t \;\ldots\; (5)$$

These expressions are not what is normally called simple. The amplitude of the waves $\sin \omega_0 t$ is given by a term $I_0 \cos\left(m_f \sin p_0 t\right)$, in other words, we have a trigonometrical function of a trigonometrical function, and we can represent this again as a series of continuous waves of different frequencies. Thus :

$$\cos\left(m_f \sin p_0 t\right) = a_0 + a_2 \cos 2\, p_0 t + a_4 \cos 4\, p_0 t + \;\ldots\; (6)$$

and $$\sin\left(m_f \sin p_0 t\right) = a_1 \sin p_0 t + a_3 \sin 3\, p_0 t + a_5 \sin 5\, p_0 t + \ldots (7)$$

where the constants a_0, a_1, a_2 are proportional to Bessel coefficients which are usually written as $J_0\left(m_f\right)$, $J_1\left(m_f\right)$, $J_2\left(m_f\right)$. Hence $I_0 \sin\left(\omega_0 t + m_f \sin p_0 t\right)$ can be written as :

$$\begin{aligned} I = {} & I_0 \,.\, J_0\left(m_f\right) \sin \omega_0 t \\ & + I_0 \left[J_1\left(m_f\right) \left\{ \sin\left(\omega_0 + p_0\right)t - \sin\left(\omega_0 - p_0\right)t \right\} \right] \\ & + I_0 \left[J_2\left(m_f\right) \left\{ \sin\left(\omega_0 + 2p_0\right)t + \sin\left(\omega_0 - 2p_0\right)t \right\} \right] \\ & + I_0 \left[J_3\left(m_f\right) \left\{ \sin\left(\omega_0 + 3p_0\right)t - \sin\left(\omega_0 - 3p_0\right)t \right\} \right] \\ & + \text{etc.} \ldots\ldots \end{aligned}$$

We thus have a large series of side frequencies in pairs at frequencies $\frac{p_0}{2\pi}, \frac{2p_0}{2\pi}, \frac{3p_0}{2\pi} \ldots$ from the main frequency $\frac{\omega_0}{2\pi}$.

The amplitudes of these side frequencies do not follow a simple law, and again there is an infinite number of them. Further, it is to be observed that the phase relationship of the various pairs of side bands differ, so that the side frequencies $\pm \frac{2p_0}{2\pi}, \pm \frac{4p_0}{2\pi} \ldots$ have the same phase relation as in the case of amplitude modulation ; whilst the side frequencies $\pm \frac{p_0}{2\pi}, \pm \frac{3p_0}{2\pi} \ldots$ have an entirely different phase relation. There is little wonder that engineers and scientists considered that such a system would give great distortion, and still not be free of interference, as a very wide frequency band seemed necessary.

There is a feature which seemed to afford some hope, that if we keep the deviation small, the amplitude of the side frequencies $\pm \frac{2p_0}{2\pi}, \pm \frac{3p_0}{2\pi} \ldots$ become very low and we were left with only one pair of side frequencies, $\pm \frac{p_0}{2\pi}$, just as in the case of amplitude modulation. It can be understood, therefore, that this appeared to be a melancholy conclusion, for then no advance seemed possible, and the best course was to come back to amplitude modulation.

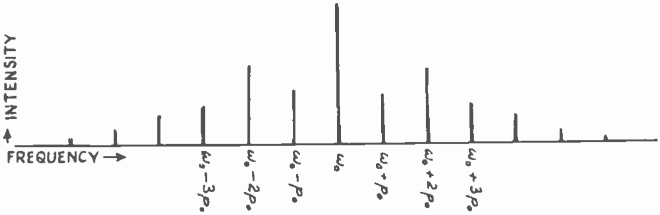


Fig. 8.—Side bands produced by frequency modulation.

This is precisely the stage where a very brilliant conception was introduced by Armstrong.[14] It had been generally assumed that we must not employ a waveband which is too wide for a single service. The reasons for this universal view were the necessity to economise the available bands of frequency, and further because the noise level which is obtained with sensitive amplifiers was considered to be proportional to the band width. Armstrong suddenly reversed this outlook and decided to employ a wide channel of 70 to 100 kc/s for a single service in place of the usual band width of 10 or 20 kc/s.

Obviously, then, for such wide deviations it is necessary to employ a wide band receiver which should give uniform response over the whole band, as many side bands are involved for a single modulation frequency. This receiver must respond to most or all of them and there should be faithful reproduction.

He then had to show that, contrary to prevalent scientific opinion, such a wide band receiver would not give a corresponding increase in the noise level. The general noises are assumed to be spread evenly over the whole wave band. The carrier frequency moves periodically over this wave band, and thus any single disturbing wave is only within audible range of the carrier for a comparatively small portion of the operating time, and its effect is thus reduced. There are many such interfering waves, and as they are spread over the whole waveband, they beat together to contribute in the detector to the rough hissing hoise. This is where the effect of demodulation makes itself felt, the same principle of demodulation which is very effective in the Stenode. As most of the noises are at a frequency separation from the carrier, which is supersonic, the beats between interfering waves are demodulated or made ineffective.

Thus it was shown that, with wide band frequency modulations, the noises are not large as was generally anticipated and in fact the noise level diminishes as the width of the band increases.

The recognition of these principles constituted the practical step towards successful frequency modulation. Naturally other principles had to be employed, such as amplitude limiting, but it had always been recognised that limiting would be necessary in frequency modulation systems in order to eliminate disturbances of an amplitude nature.

On these principles, Armstrong developed a practical system. His transmitting system contains certain features which need reference here. The first feature is his method for obtaining true frequency modulation. Actually he does this by first obtaining a phase modulation, which is then converted to frequency modulation, after which frequency multiplication is employed in order to obtain the very large frequency deviation of 50 kc/s or more.

Phase modulation is in nature somewhat similar to frequency modulation, as it involves a phase displacement positively and negatively at the rate of the modulation frequency. Such a phase displacement, however, also involves a frequency variation and, in fact, the frequency deviation is proportional to the rate of change of phase. I would particularly refer to Howe's[15] description in *The Wireless Engineer* on the relations between frequency and phase modulation.

Phase modulation can be produced from amplitude modulation, by deleting the carrier $I_0 \sin \omega_0 t$ from expression 3 and replacing it in quadrative as $I_0 \cos \omega_0 t$ (see Appendix 3). When this is done, amplitude variations are practically abolished, and we have a carrier of constant amplitude whose phase changes at a rate determined by the modulation frequency. Now the maximum phase displacement is the same for all modulation frequencies of the same amplitude, and then as the corresponding frequency deviation is proportional to the rate of change of phase, we have the frequency deviation much greater for high frequency than for low. The essence of a frequency modulation system is that the deviation must be the same for all modulation frequencies of the same amplitude. Thus, we must make the actual phase displacement inversely proportional to the modulation frequency. Armstrong, therefore, distorts the modulation before applying it to phase modulation, and he does it by putting the speech through an amplifier, whose amplification is inversely proportional to frequency. In this way he obtains a frequency deviation which is independent of modulation frequency but which depends only on amplitude.

It is important to note the difference between frequency and phase modulation. Both systems operate at constant amplitude, both produce a change of frequency on modulation, but frequency modulation gives the same frequency deviation for all frequencies of the same amplitude, whereas phase modulation gives a frequency deviation which is proportional to modulation frequency. This is of importance in assessing the relative merits of the two systems.

Interference with Frequency and Phase Modulation Systems

With a knowledge of the method by which Armstrong made frequency modulation practical it becomes possible to investigate the advance made towards the elimination of interference. Under certain conditions Armstrong's system overcomes interference in a most remarkable manner.

From the preceding outline of frequency modulation systems where a complicated system of side bands exists, it is to be expected that interference will occur. If, for instance, we consider single continuous waves of a definite frequency somewhere inside the operating wave band, reference to Fig. 8 will show that it will be near one or other of the side bands of the desired programme. If the operating wave band is 100 kc/s, and the desired carrier sweeps periodically over the whole band, it will be within audible range of the interfering continuous wave only for a small portion of the operating time, and thus the interference will be reduced. This, however, is not a very elegant method of description, particularly if the quantitative value of the interference is desired. It is preferable to consider Fig. 8 and to calculate the interference produced between the interfering continuous waves and each of the desired side bands. For wide operating bands the interference is produced only with the desired side bands which are within audible range, and thus the resultant interference is small. The actual amplitudes of the desired side bands are also of importance, and in general, the further removed a side band is from the mean frequency, the lower is its amplitude. Further, the actual amplitudes of the desired side bands depend on the deviation. Thus the wider the operating band, the more side bands for a desired modulation frequency become effective, and as the number of side bands increases, the amplitude of these side bands generally diminishes. Thus the wider the operating band, the less is the interference which is produced by a single continuous wave.

When two continuous waves of a frequency separation which is audible are present simultaneously, each of them has its direct interfering effect reduced for wide deviations, but another form of interference remains to be considered, this being the audible beat note between the two waves. If each of the interfering waves is of a lower amplitude than the desired carrier, then this beat note is demodulated and made ineffective. This demodulation, as applied to frequency modulation, is discussed in a little more detail below.

Thus any single continuous waves or combinations of such, of different frequencies, produces an amount of interference which diminishes as the operating wave band increases, provided that each of them is of lower amplitude than the desired carrier.

Armstrong emphasises this advantage particularly as regards amplifier noises ; in fact, the signal to noise ratio increases rapidly as the width of the band increases.

Thus, if it is possible to reserve a wide band of 100 kc/s for a single programme, the reception can be practically free of noise.

Those who wish to investigate this subject mathematically can find an excellent treatment by Keall.[2] He treats the subject from the aspect of the complicated system of side frequencies. Armstrong himself points out that the Interfering Programme Demodulation has some considerable influence, and we might usefully attempt to follow up the preceding graphical description to see actually how the remarkable efficiency of frequency modulation really arises.

There are certain engineers who believe that any advantages of frequency modulation must arise from the limiting which is employed, as they believe that amplitude modulated waves, heterodynes and random noises produce nothing but amplitude variations. Were this true, it would be easy to understand why all amplitude effects could be eliminated, but we would still have to account for another remarkable effect that under certain conditions other frequency modulation services are also eliminated. In fact, we can have two frequency modulation services on the identical carrier wave, and we can at times receive one of them without any appreciable interference from the other.

Certain forms of amplitude modulation also produce phase and frequency modulation. In particular, a heterodyne effect produces both amplitude and phase modulation. Thus, if we have a heterodyne produced by two continuous waves, as in Fig. 1b, the amplitude varies periodically according to the beat frequency, and further we have the fact that the periods of time at which the voltage is zero varies from oscillation to oscillation, giving us, therefore, a phase modulation. Thus, if we apply a limiting device to this heterodyne to produce constant amplitude we still do not produce continuous waves, but waves which are phase modulated.

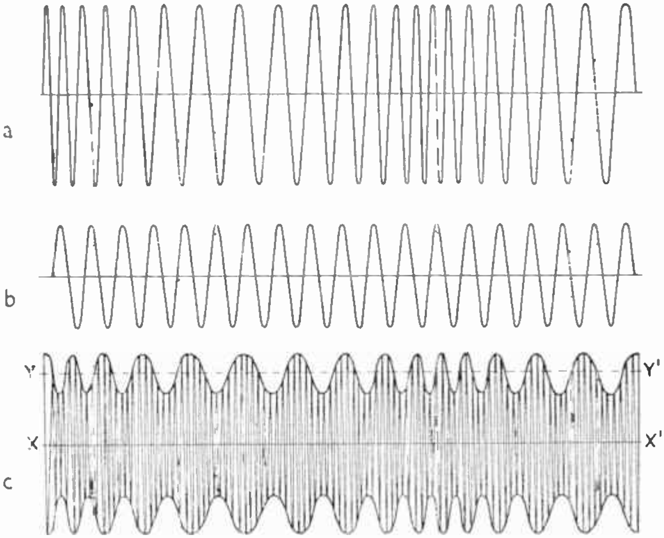


Fig. 9.—Heterodyne effects produced by the combination of frequency modulated waves at (a) *and continuous waves at* (b). *The heterodyne beats* (c) *are frequency modulated.*

The reason why a heterodyne produces phase modulation is given in Appendix 1. Thus limiting removes amplitude variations, but in many cases it has still left us with the heterodyne effect as a phase modulation, which is of a similar nature to the desired frequency modulation signals. The reason why even the phase modulation effects of the heterodyne are overcome is concerned with the effects at the rectifier. In this connection it must also be remembered that a limiter is also of a somewhat similar nature to a rectifier.

Consider the case of frequency modulated waves (Fig. 9a), together with a steady continuous wave (9b). We shall have a heterodyne produced as in Fig. 9c, where the heterodyne envelope is frequency modulated. In other words, if the total deviation of the waves in 9a is 1,000 c/s the heterodyne effect (9c) will vary in pitch. Thus if the waves of 9a vary between 101,000 and 100,000, and if the waves 9b have frequency 100,200, the heterodyne effect will vary from 800 to 0, then to 200 back to 0, and to 800, and so on, and this would be an unpleasant effect. However, if the waves 9a vary between 1,000,000 and 1,050,000, and the waves 9b were of frequency 1,020,000, the heterodyne would vary from 30,000 to 0, to 20,000 back to 0, and 30,000, and we should only hear it for the periods when it is below 5,000 c/s, when its effect in total would be diminished.

Now suppose the steady waves 9b are amplitude modulated, or in the equivalent that we have two heterodyne waves present which are, say, 300 c/s apart in frequency. Then it is easy to see that the heterodyne effect of 9c now becomes modulated by the new modulation frequency, and its form is shown in Fig. 10c, an effect similar to that of Fig. 6e. When we rectify Fig. 10c, we are left with its upper half, and the new modulation cannot be effective for similar reasons to those of Fig. 6e. In other words, the modulation of the continuous waves of 10b becomes demodulated. Thus, when applied to a rectifier, we delete the whole lower half of Fig. 10c, that is, we are left with the effects above the line XX_1. The modulation of the interfering waves is given by the envelopes abc, but also there is a similar envelope below the mean value YY_1. The resultant interfering modulation is thus given by the mean value of the two envelopes abc and $a^1 b^1 c^1$ and as in the case of Fig. 6e, this is practically constant, meaning that the interfering effects have practically vanished.

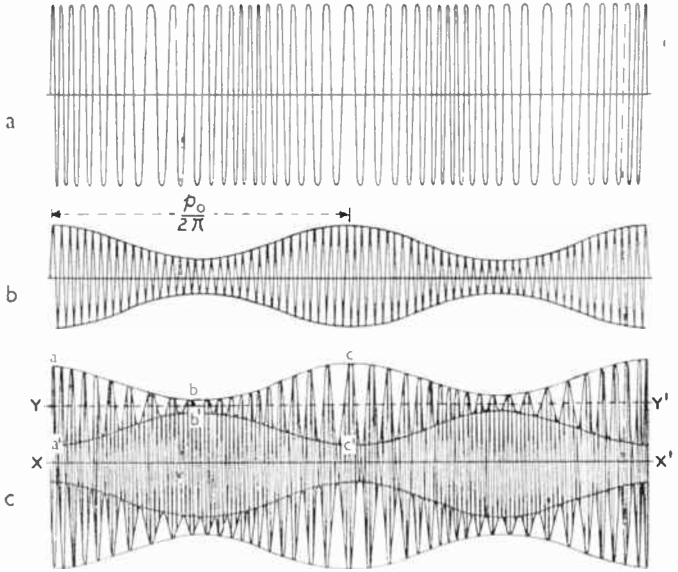


Fig. 10.—Demodulation of interfering programme with frequency modulation system. (a) *and* (b) *are as in Fig. 9, but* (b) *is amplitude modulated at frequency* $\frac{p_0}{2\pi}$. *The heterodyne beats at* (c) *are frequency modulated and amplitude modulated. The interfering effects are demodulated at the receiver.*

This is not the complete story in the case of frequency modulation as the interfering modulation which we have just shown to be removed is of an amplitude type, and in any case it would be eliminated by the limiter. The important thing is that, as already shown, many forms of amplitude modulation have phase modulation associated with them. The phase variations due to the interfering modulation must correspond to the amplitude modulations of Fig. 10b and thus, after limiting, we shall have the desired frequency modulations, with phase modulations superimposed which are of a nature which corresponds with the double envelope of Fig. 9b.

When this complex effect is applied to the frequency discriminator, in order to convert the frequency variations into amplitude variations, we shall again have the interfering effects represented by a curve similar to the upper half of 10c. Then when applied to the rectifier, the interfering effects will be demodulated.

Limitations of Frequency and Phase Modulation

It should be clear why noise effects are reduced or eliminated by employing a wide deviation frequency modulation system. However, when other forms of interference are encountered, such as other radio services, the conditions are not so ideal, because the level of the interference may be much higher. A number of peculiarities need reference under such conditions. Interfering waves can produce distortion of the desired programme. Again, if the interfering frequency is removed from the mean operating frequency by, say, 30 kc/s, it will have no effect on the desired programme, unless that programme is strong, because the deviation of a frequency modulation programme increases with the strength of modulation. Most important of all is the fact that it is absolutely essential that the desired carrier must be stronger than the level of the interference.

In many cases this is possible, particularly if the interference is merely of the general noise type. From the preceding description it can be understood why this restriction must be present in Armstrong's system, and this is because he relies on the demodulation principle when weak interfering waves at a supersonic frequency separation are demodulated by a strong carrier. Thus, if we have two or more services arriving simultaneously at a receiver it is not easy to see how we can receive the weaker of these services. With Armstrong's system we can hardly obtain any of the benefits of selectivity as it is necessary to have the receiver tuned to receive waves of a wide band of 70 to 100 kc/s.

GENERAL

Most of the proposals to make greater use of the ether as a communication medium during the last twenty years have been described. These can be summarised as follows :

1. **Employment of shorter wavelengths.**—This has been one of the major developments of the last 20 years and it is still proceeding. It is outside the scope of this discussion.

2. **Single side band transmission.**—There have been two methods :

(*a*) Transmission of one side band with the carrier :

(*b*) Transmission of one side band without the carrier.

Both methods give a saving of space in the available gamut of frequencies, requiring only half the frequency band of ordinary amplitude modulation. Both give a saving of power at the transmitter. Method (*b*) saved 75 per cent. of the power whilst method (*a*) saves only 25 per cent. Method (*a*) could be employed for general reception even for the most elementary broadcast receivers. Method (*b*) has been restricted to commercial services, as it is necessary to supply the carrier at the receiver, a step which in practice is far from attractive, particularly in broadcasting.

3. **Use of High Selectivity.**—For a considerable time it was considered that there was a limit to the selectivity of the circuits that could be employed. It has been shown by the Stenode that it is possible to use the highest selectivity and that it is possible to employ correction in the audio frequency circuits to correct the distortion. This correction can be employed at the transmitter or at the receiver.

High selectivity reception has an advantage which is outstanding ; that it makes the desired carrier very much stronger than any other waves received. The importance of this fact has even now not been sufficiently appreciated. A strong wave demodulates weaker waves in a rectifier and thus gives one of the most powerful means for eliminating interference. Use of selectivity enables us to concentrate on a weak signal and to increase its carrier to such an extent that it becomes strong with regard to powerful interference, and thus it enables us to demodulate such powerful interfering signals.

The Stenode thus possesses a very important feature which is not possessed by other systems hitherto employed, not even the well-known band pass receivers. The Stenode thus eliminates much interference, but it does not deal with heterodyne interference generally. It is, however, quite easy to employ a quartz crystal as a single side band receiver, and thus heterodyne noise effects can be cut down by 50 per cent.

Inverse Stenode Transmission gives still further progress. By transmitting on the assumption that high selectivity receivers are to be used, we can apply correction at the transmitter and transmit the higher side frequencies at much greater level with regard to the lower side frequencies than normally. Then reception is simple and we obtain a very considerable improvement in the signal to noise ratio.

Further, this method will give a gain in the efficiency of the transmitter, for we need only transmit a low percentage of the normal carrier and we can rely on the fact that the high selectivity of the receiver will accentuate it, thus making it again very strong.

Single Side Band Inverse Stenode Transmission.—With Inverse Stenode transmission there is no necessity to transmit both side bands, and we can transmit merely one side band and a small amount of the carrier when interference is eliminated to an extent that is probably not exceeded by any other system.

Frequency and Phase Modulation.—These methods give side frequencies of a much more complicated nature than amplitude modulation. Each simple modulation frequency p_0 produces a single pair of side frequencies at frequency separation p_0 from the carrier in the case of amplitude modulation, but in the case of frequency and phase modulation there are additional side frequencies at $2p_0, 3p_0, 4p_0$ . . . frequency separation from the mean frequency.

Armstrong introduced a brilliant conception by employing this complicated side frequency spectrum. He made the deviation so wide that he received practically the whole of the side frequencies, and thus obtained reception free from distortion.

Further, in so doing, he was able to employ the great advantage of interference demodulation, as all interfering waves occurred at supersonic frequencies for a large portion of the operating time.

Thus Armstrong's wide deviation system cuts down interference in a remarkable manner, particularly the random receiver noise when these are weaker than the desired waves. Interference is obtained, however, and this becomes more pronounced as the deviation is made smaller. A peculiarity of the interference is that a single interfering wave produces many interfering waves by a process similar to cross-modulation with the individual side frequencies of the frequency modulation system. This interference is more pronounced with phase than with frequency modulation.

Directional Methods.—The soundest principles for eliminating interference are those of directional wireless. Directional transmissions concentrate the energy into a restricted geographical area, but such a form of transmission has not been employed to the extent that appears to be necessary in view of the importance of the general subject. In fact, it has only been employed so far for short wireless waves.

Directional reception has been employed occasionally to eliminate interference. The normal method is to employ a simple loop aerial which gives zero reception for waves arriving along one line on the earth's surface. Certain work has been done to produce a wireless reception system which will receive only in a definite arc. The work of the G.P.O. in this respect deserves notice as they have actually employed such a receiver for long-wave reception which would receive only in an arc of about 60°.

Such directional reception is naturally easier to employ for short waves, but as long and medium waves are also of very great importance, it appears as if the ultimate solution to the problem of eliminating wireless interference will come from the production of a receiving system which will receive waves over the narrowest arc.

SUMMARY

Employing the principle of modulation, considerable improvement in the elimination of interference in wireless communication has been effected by three distinct methods :

1. Single side band transmission ;
2. High selectivity of the receiving system ;
3. Frequency modulation.

It is to be observed that much of the benefit from the latter two methods, high selectivity and frequency modulation, arise from the same cause : that of the demodulation of weak waves by strong waves.

None of these methods has so far been developed practically to the greatest extent. It is possible that a combination of the methods of a single side band transmission and high selectivity of the receiver will give results as satisfactory as can be obtained in any other way, apart from directional methods.

Times of great world upheaval like the present usually compel us to consider radical changes in our mode of living, and it is quite possible that changes in our Broadcasting System might be due for consideration. In any such change the merits of the various systems of Modulation must be carefully weighed. Whatever is done must allow us to overcome interference generally to the best advantage, and must allow us to accommodate as many services as possible in the available frequencies.

The public have a vested interest in the medium wave bands, where there are not too many available frequencies, and this right of the public to the use of the medium waves must be jealously guarded.

A wide band frequency modulation system such as Armstrong's is ideal so long as that wide band can be kept free of other transmissions, and this might be practicable on very short waves. The public, however, must have a wide choice of services, and the other improvements which modulation principles offer to us, such as the single side band system and the use of high selectivity, should be carefully considered before any radical change in Broadcasting is introduced.

Improvements in the elimination of interference by the principles of modulation are certainly substantial, but up to the present they have not made it possible to accommodate many services in a single channel, and it is quite possible that the next progressive step in this direction will result from the skilful use of directional wireless.

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APPENDIX 1

Phase Modulation Produced by a Heterodyne

Let strong waves A sin $\omega_0 t$ and weak waves B $\sin(\omega_0+q_0)t$ arrive together at a linear detector.

Let X $\quad A \sin \omega_0 t + B \sin(\omega_0+q_0)t$ ....(1)

$$(A+B\cos q_0 t)\sin \omega_0 t + B \sin q_0 t \,.\, \cos \omega_0 t$$

$$\sqrt{(A+B\cos q_0 t)^2 + (B \sin q_0 t)^2} \,.\, \sin(\omega_0 t+\psi)$$

$$\sqrt{A^2+B^2+2AB\cos q_0 t} \,.\, \sin(\omega_0 t+\psi)$$

where $\tan \psi \quad \dfrac{B \sin q_0 t}{A+B\cos q_0 t}.$

Thus X $\quad W \sin(\omega_0 t+\psi)$ ....(2)

where the amplitude $W = \sqrt{A^2+B^2+2AB\cos q_0 t}$ ......(3)

The curve W is the envelope of the resultant complex oscillation. It varies in amplitude with $\cos q_0 t$, and thus its maximum and minimum amplitudes are $(A+B)$ and $(A-B)$ respectively.

The phase ψ is not constant, and it varies with $q_0 t$. Thus ψ varies periodically between values given by $\tan\psi = +\frac{B}{A}$ and $\tan\psi = -\frac{B}{A}$, and this is a phase modulation, whose magnitude obviously increases when B increases.

APPENDIX 2

Appleton and Booharіwalla's Explanation of Demodulation

Following on from Appendix 1, where strong waves $A \sin \omega_0 t$ and weak waves $B \sin(\omega_0 + q_0)t$ produce a resultant effect, $X = W \sin(\omega_0 t + \psi)$, let us assume that the frequency difference of the two waves is supersonic. We are to allow the weak carrier B to be modulated, when the rectified output will be calculated.

To evaluate this, the mean value of X is first obtained.

$$X = \sqrt{A^2+B^2+2AB\cos q_0 t}$$

$$= \sqrt{A^2+B^2}\left[1+\frac{AB\cos q_0 t}{(A^2+B^2)}-\frac{1}{2}\frac{A^2B^2\cos^2 q_0 t}{(A^2+B^2)^2}+\ldots\right] \ldots\ldots (4)$$

The value of X varies periodically at a supersonic frequency, and its mean value $\bar{X}$ is given by

$$\bar{X} = \sqrt{A^2+B^2}\left[1-\frac{1}{4}\frac{A^2B^2}{(A^2+B^2)^2}+\ldots\right] \ldots\ldots\ldots\ldots\ldots (5)$$

When applied to a linear detector, $\bar{X}$ is proportional to the mean current.

If the weak waves B are now modulated, or have their amplitude changed periodically from B to $B \pm \triangle B$, we can find the change in the mean value $\bar{X}$ by obtaining $\frac{\triangle\bar{X}}{\triangle B}$.

$$\bar{X} = \left[\sqrt{A^2+B^2}-\frac{1}{4}\frac{A^2B^2}{(A^2+B^2)^{3/2}}+\ldots\ldots\right]$$

$$\frac{\triangle\bar{X}}{\triangle B} = \left[\frac{B}{A}\cdot\frac{1}{\left(1+\frac{B^2}{A^2}\right)^{1/2}}-\frac{1}{2}\cdot\frac{B}{A}\cdot\frac{1}{\left(1+\frac{B^2}{A^2}\right)^{3/2}}+\frac{3}{4}\cdot\frac{B^3}{A^3}\cdot\frac{1}{\left(1+\frac{B^2}{A^3}\right)^{5/2}}\right] (6)$$

When B is small, so that $\frac{B}{A}$ is much smaller than unity, we have

$$\frac{\triangle\bar{X}}{\triangle B} = \frac{1}{2}\cdot\frac{B}{A}, \text{ or } \triangle\bar{X} = \frac{1}{2}\cdot\frac{B}{A}(\triangle B)$$

$\triangle B$ is the change which would have occurred if the strong waves A had been absent. The presence of the strong waves A reduces this change of mean current to $\frac{1}{2}\cdot\frac{B}{A}(\triangle B)$.

APPENDIX 3

Production of Phase Modulation from Amplitude Modulated Waves

Waves $I_0 \sin \omega_0 t$ modulated by $\cos p_0 t$ give us amplitude modulated waves.

$$I = I_0 \sin \omega_0 t + i_0 \sin(\omega_0 + p_0)t + i_0 \sin(\omega_0 - p_0)t \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Let us change the phase of the carrier to $I_0 \sin(\omega_0 t + \phi)$, then

$$I = I_0 \sin(\omega_0 t + \phi) + i_0 \sin(\omega_0 + p_0)t + i_0 \sin(\omega_0 - p_0)t \ldots\ldots\ldots\ldots (2)$$

When rectified at a square law detector we obtain an output B, where

$$\begin{aligned} B &= I_0 i_0 \cos(p_0 t - \phi) + I_0\, i_0 \cos(p_0 t + \phi) \\ &= 2\, I_0\, i_0 \cos\phi \,.\, \cos p_0 t \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3) \end{aligned}$$

Thus for $\phi = 0$ we obtained the maximum output, but for $\phi = 90°$ the output at frequency $\frac{p_0}{2\pi}$ is zero.

If we change the phase of the carrier from $I_0 \sin \omega_0 t$ to $I_0 \cos \omega_0 t$, we obtain

$$I_1 = I_0 \cos \omega_0 t + i_0 \sin(\omega_0 + p_0)\, t + i_0 \sin(\omega_0 - p_0)t \ldots\ldots\ldots\ldots (4)$$

which we should expect to have a constant amplitude and to be phase modulated. However, the amplitude is not absolutely constant, and we shall determine the envelope.

$$\begin{aligned} I_1 &= I_0 \cos \omega_0 t + 2 i_0 \cos p_0 t \,.\, \sin \omega_0 t \\ &= \sqrt{I_0^2 + 4 i_0^2 \cos^2 p_0 t} \,.\, \cos(\omega_0 t - \psi) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5) \end{aligned}$$

$$\text{where } \tan\psi = \frac{2\, i_0 \cos p_0 t}{I_0} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

If $A = \sqrt{I_0^2 + 4 i_0^2 \cos^2 p_0 t}$, we have

$$I_1 = A \cos(\omega_0 t - \psi).$$

There is phase modulation, given by $\tan\psi = \frac{2\, i_0 \cos p_0 t}{I_0}$, and this increases as $\frac{i_0}{I_0}$ increases.

$$\begin{aligned} \text{The amplitude } A &= \sqrt{I_0^2 + 4 i_0^2 \cos^2 p_0 t} \\ &= I_0 \left(1 + \frac{4 i_0^2}{I_0^2} \cos^2 p_0 t\right)^{1/2} \\ &= I_0 \left(1 + \frac{2 i_0^2}{I_0^2} \cos^2 p_0 t - \frac{2 i_0^4}{I_0^4} \cos^4 p_0 t \ldots\ldots\right) \ldots\ldots (7) \end{aligned}$$

Where $\frac{i_0}{I_0}$ is small, which is the normal case of amplitude modulated waves, we can write this as

$$\begin{aligned} A &= I_0 \left(1 + \frac{2 i_0^2}{I_0^2} \cos^2 p_0 t\right) \\ &= I_0 \left(1 + \frac{i_0^2}{I_0^2} + \frac{i_0^2}{I_0^2} \cos 2 p_0 t\right) \end{aligned}$$

and the complete representation of equation (4) becomes

$$I_1 = I_0 \left(1+\frac{i_0^2}{I_0^2}\right) \cos\left(\omega_0 t-\psi\right) + \frac{i_0^2}{I_0} \cos 2\, p_0 t \,.\, \cos\left(\omega_0 t-\psi\right) \ldots\ldots\ldots (8)$$

Thus we have true phase modulated waves with the addition of amplitude modulated waves $\frac{i_0^2}{I_0} \cos 2p_0 t \,.\, \cos (\omega_0 t-\psi)$. The amplitude modulated waves appear principally at double the modulation frequency and have small amplitude if $\frac{i_0}{I_0}$ is small. (For present purposes we can neglect the phase variation of these waves, because of the small magnitude.)

This is instructive in helping to understand why frequency or phase-modulated systems must have a complex system of sidebands. As the expression (8) contains an amplitude modulation term, we can only produce true phase modulated waves of constant amplitude if we add a term

$$-\frac{i_0^2}{I_0} \cos 2p_0 t \,.\, \cos\left(\omega_0 t+\psi\right) \ldots\ldots\ldots\ldots\ldots\ldots (9)$$

Thus in addition to the two sidebands of expression (4) we must add two further sidebands $(\omega_0+2p_0)t$ and $(\omega_0-2p_0)t$, which are of an amplitude modulation type, in order to have constant amplitude.

It is thus observed that when the phase modulation is very small, which according to equation (6) occurs when $\frac{i_0}{I_0}$ is very small, we have only one pair of sidebands of a frequency modulation type. This corresponds to very small deviations.

When the phase modulation is somewhat larger, which means somewhat larger frequency deviations, we must introduce a second pair of sidebands of an amplitude modulation type.

As the phase modulation increases again, more and more sidebands become necessary. It is possible to develop this to evaluate the terms of higher modulation frequency by taking into consideration the terms we have so far neglected in equation (7), and by reconsidering expression (9) and taking its phase modulation into account.

DISCUSSION

Mr. Washtell :

" Does the asymmetric side band type of transmission using one complete sideband and the low frequency portion of the other give a practical advantage over single side band in the replacement of the carrier in the correct phase for subsequent rectification at the receiver ? "

Mr. Swinton :

" A very important aspect of frequency modulation was the question as to whether it allows us to accommodate more services in the ether. Although the Armstrong system employs a wide band for a single service, the ' Captive ' effect enables us to receive the stronger of two transmissions to the exclusion of the weaker. The two stations could be operating on the same frequency, each, therefore, giving a local service."

Dr. Robinson intimated at this point that this was so.

Mr. Swinton :

" Will the stenode give better results against local interference ? "

Mr. Beattie :

" Much credit is due to Dr. Robinson for his proposal when he introduced the stenode of a system of transmission in which pre-emphasis is given to the higher modulation frequencies. In Dr. Robinson's system this will certainly enable the benefits of high selectivity to be obtained without undue complications of the receiver. In fact, we might assume that by this proposal he should have some of the credit for the later development of frequency modulation. It is interesting to observe that a similar system of transmission was put forward by Crosbie of R.C.A. This general feature of pre-emphasis at the transmitter undoubtedly needs much more attention from engineers. Another example of the advantages which might arise from such radical changes at the transmitter is given by the system of Pulse Modulation which appears to have advantages similar to those of frequency modulation. It would be interesting to follow up the discussion on frequency modulation with regard to aspects such as distortion, and further as to whether a frequency analyser has been employed to analyse the side band system."

Mr. Tibbs :

" The answer to Mr. Beattie's question regarding the analysis of a frequency modulation spectrum was given in the Proc. I.R.E., August, 1940, where the side band system was experimentally verified."

Mr. Levy :

Agreed with Dr. Robinson that one of the chief tasks of radio engineers was to show how more services could be accommodated in the available wave bands, and the employment of amplitude and frequency modulation services together should enable progress to be made towards this object. This should at least allow us to double the number of services. It was interesting to note how progress towards the elimination of certain types of interference was made by Armstrong by deliberately employing a wide band for a single service. The pulse transmission already referred to in this discussion also gave good results in some respects, but at the expense of a wider wave band.

Mr. Ransome :

Referred to the desirability for linearity in amplification. It was well known that if a high frequency amplifier were not linear, there *would* be inter-modulation between the desired wave and waves on the neighbouring channel. He remarked that, whilst the Stenode eliminated the modulation of a neighbouring channel, it was essential that the amplifier should be linear, otherwise the benefits of the high selectivity may be vitiated.

Mr. West :

" In a system where inverse amplification is used at the transmitter, will side-band splash be accentuated ? "

DR. J. ROBINSON

Mr. Pack :

" Does frequency modulation improve transmission from the point of view of fading? '

Mr. Lee :

" It would be interesting to have some definite facts about the performance of a frequency modulation system in the presence of man-made static ; and further as to whether such interference can be handled on the assumption that it is of a heterodyne nature."

Mr. Bedford :

" Dr. Robinson has explained a difficult subject in a very clear manner. He has given to-night a description of the stenode, showing the types of interference which it eliminates, which he characterises as programme interference. His explanation of demodulation is exceptionally lucid, and he quite rightly suggests that this is of very great importance in radio generally. I agree with him that a new term should be introduced for it, and I suggest the term " Unmodulation." Dr. Robinson's explanation of Unmodulation was so clear that it is surprising that Mr. Williams should ask why a carrier does not eliminate its own modulation."

Dr. Robinson (replying) :

" My object to-night was to attempt to explain certain features of modulation which hitherto have not been thoroughly understood by many engineers. In particular, I wished to bring forward that very important principle which was originally called Demodulation, but which needs a new name. I believe Mr. Bedford's term " Unmodulation " to be very suitable. It is pleasing to hear from Mr. Bedford and certain other speakers that I have succeeded in making this subject easy to understand, and further that I have made clear the theory and performance of the stenode and how its efficiency depends on Unmodulation, and again how this same rectifier effect is of importance in frequency modulation. That modulation is a wide and complex problem is shown by the variety and pertinence of the general discussion

" For example, Mr. Lee draws attention to man-made static, pointing out that we urgently need some accurate observations on the relative merits of amplitude and frequency modulation in dealing with such interference. He further raises the point of theory as to whether such interference can be explained by assuming it to be of a heterodyne nature. Under many conditions, particularly when its level is not to high, it can be explained in this way, and frequency modulation should minimise it under such conditions.

" I am pleased to have Mr. Beattie's commendation on the part I played in bringing forward the method of pre-emphasis at a transmitter. His reference to the influence of interfering waves in causing distortion of the desired signals in frequency modulation was referred to only briefly in my paper because of the need to keep the scope of the paper within reasonable limits, but I referred to other publications such as Keall's paper for this and other aspects.

" With regard to Mr. Ransome's suggestion, it had always been recognised with the Stenode that it was advisable to place the highly selective circuit at the earliest part of the intermediate frequency amplifier, in order to avoid or to minimise any such effects.

DR. J. ROBINSON

" Mr. West was very appreciative of Stenode transmission which, in his view, should increase the signal to noise ratio. He is quite right, however, in his view that there was the possibility that side band splash may be somewhat increased owing to the fact that the higher frequency modulations were at a greater amplitude. This, however, in practice should not introduce any serious difficulty, if the channels were kept at their correct frequency spacing and if the receiver were so designed that it contained a cut-off in the low frequency amplifier at a suitable frequency.

" Mr. Pack asked about the behaviour of frequency modulation fading. It was of interest to note that the principal use of frequency modulation so far, had been for comparatively short distance communication, where fading should not be observed. For very long distance communication, the wide deviation systems would most probably show peculiar effects under conditions of fading. For instance, selective fading introduced time delays for certain frequencies at irregular intervals which would introduce changes of phase.

" Mr. Washtell raises the question of asymmetric side band communication. Undoubtedly such a system will allow satisfactory reproduction, and the implied suggestion in the question that the phase of the carrier and the phase of reproduction may not be correct need not prevent such a system from operating. However, as it is quite easy to obtain single side band transmission, and as by the use of a double quartz crystal band pass it is easy to obtain a single side band receiver, there seems to be no reason why, when a change of our broadcasting system is considered, we should worry about asymmetric side bands, as a straightforward single side band system or the single side band stenode system would be preferable."

The

British Institution of Radio Engineers

GRADUATESHIP EXAMINATION

PASS LIST—MAY, 1942

In publishing the following Pass List we offer to each candidate sincerest congratulations and wish them all success in their future careers. We hope that eventually every one of them will become qualified for membership of the Institution.

This list includes candidates who are exempt from, or who have previously passed part of, the examination and who have now passed in the remaining subjects.

Success in the examination does not, of itself, obtain membership.

Passed entire Examination

Passed with Distinction

John Pollard, B.Sc. (S.)	Liskeard, Cornwall

Passed with Credit

Kenneth Humphreys (S.)	London, S.E.12

Passed Parts 2, 3 *and* 4 *only*

Charles Heywood, M.A., B.Sc.(Hons.), A.K.C.	Dudley, Worcs.

Passed Parts 2 *and* 4 *only*

Gerhard Muller	London, N.19

Passed Parts 3 *and* 4 *only*

George D. Bolam (S)	Newcastle-on-Tyne
Alan J. Edwards (S.)	Birmingham
Michael Hamilton (S.)	Bournemouth
Dennis W. Heightman	Clacton-on-Sea
Kenneth E. James (S.)	Bury, Lancs.
Laurence E. Taylor (S.)	Swindon
William H. Wentworth	Greenford

Passed Part 1 *only*

Albert T. Cartwright	Aberdeen

Passed Part 2 only

Bruno Muller	London, S.W.20

Passed Part 3 only

Raymond Blouet	Darlington

Passed Part 4 only
(Optional Subject)

Ronald Everson, B.Sc.(Hons.)	Bolton
Ernest F. Piper, A.M.I.E.E. (S.)	West Hove, 3

THE Brit.I.R.E. RADIO SERVICING CERTIFICATE EXAMINATION

Pass List

Cyril H. Brassington	Bristol
Cyril C. Nicolls	Petts Wood, Kent
Malcolm H. Overfield	Ashton-under-Lyne

EXAMINERS' REPORT

Part 1 (*Heat, Light and Sound and Electricity and Magnetism*).—The general standard of all papers was fairly good. Candidates, however, did not take sufficient care in confining their answers to within the scope of the questions. Answers were far from being lucid, in several cases were definitely ambiguous and very seldom expressed with clarity. In some cases, parts of the question attempted were not dealt with at all. Arithmetic showed corrections by candidates which should not have been necessary, and careless mistakes. Some diagrams directly contradicted the candidate's explanation, or where he sought to expound the theory underlying the effects as illustrated.

Part 2 (*Radio Technology*).—The best-worked paper in the entire examination, showing that the majority of candidates had a good basic knowledge of A.C. theory.

Part 3 (*Radio Engineering*).—Only 29 per cent. of the number of the candidates who attempted this examination succeeded in gaining a pass mark. Excluding two outstanding papers, the average mark obtained was very low indeed, and once again the Committee desire to draw attention to the fact that candidates seem to be badly lacking in general knowledge of fundamental principles in Radio Engineering, Transmission *and* Reception.

Candidates who failed the examination in this subject are strongly advised to make a more careful study of the syllabus.

Part 4 (Radio Receiver Design and Practice).—A few candidates revealed that they had a good grasp of design problems and also took care to give answers which showed that they realised the implications of the questions. Many answers were much too superficial, while some candidates spent valuable time in giving information which was not required by the question. In a few cases the candidates were obviously unprepared for an examination of this standard. A general criticism is that the technique of answering examination questions, including the apportionment of a certain time for each question, was bad.

Television.—The Television paper is optional ; it is presumably attempted only by candidates aspiring to professional work in this field. For this reason questions relating to Transmission and Reception were obligatory, but this arrangement appears to be the cause of lost marks.

Candidates generally failed to indicate the relations between brightness and flicker, accuracy and scanning geometry, linearity of intensity, modulation characteristics, preservation of focus with scan and modulation and the necessity for freedom from phase distortion.

In the opinion of the Committee, candidates failed in this paper through lack of preparation.

Radio Servicing.—In general, candidates failed in expressing their knowledge on paper. They appeared to have gained their knowledge from books and experience and have had no practice at answering questions on their knowledge. Several candidates failed to understand the implications of some of the questions, while slovenly answers were common.

FORTHCOMING EXAMINATIONS

The next Examination will be held on November 20th and 21st, and the 1943 Examinations on May 14th and 15th and November 19th and 20th, 1943.

The

British Institution of Radio Engineers

NOTICES

::

Obituary

We very much regret to record the death, subsequent to enemy action, of Leslie W. Westacott-Davies, of Bristol (Member), at the age of 49 years.

Trained for a mechanical engineering career, Mr. Westacott-Davies was educated at the Merchant Venturers Technical College and Bristol University, and elected a Graduate of the Institution of Mechanical Engineers in 1911. Commissioned in 1914, he served in the Royal Corps of Signals, and on return to civilian life in 1921 he commenced business as a radio component manufacturer.

For the last two years he has acted as Honorary Secretary to the south-western section of the Institution.

His son, John Westacott-Davies (Student Member), was reported missing after the battle of Singapore.

Works Discussions and Training Facilities

In view of the encouragement generally given throughout the industry to facilities for technical training in radio subjects, the Institution has had prepared a poster dealing with the Graduateship Examination and the Prizes offered for competition. Copies of this poster will be supplied to members able to arrange for its display on staff notice boards.

Technical Journals

In order to complete the Institution's copies of *The Wireless Engineer*, the issue dated November 1934 is required. Any member who is prepared to donate or sell this issue is requested to communicate with the Secretary.

Previous Issues of Journals

In order to save correspondence, will members please note that apart from the copies which may be borrowed from the library, back copies of the Institution's Journal and proceedings prior to July 1942 are no longer available.

Bound copies of previous Journals are also now out of print with the exception of a few copies of the bound Journal for 1939-40, which are available at 12s. 6d. per bound copy, post free.

The Institution's New Building

The Building Fund has been well supported by members, and through that Fund and other donations, it is hoped that the Institution will be enabled to purchase its own building.

The Fund will, of course, take many years before it can be used for that purpose. Meanwhile, the Council has been concerned with finding accommodation for the Institution which, in addition to being suitable for administrative purposes, will also provide room for expansion, library facilities and meetings. It has been resolved, therefore, that the Institution shall lease the building at 9 Bedford Square, London, W.C.1. Adequate facilities will now be available for all the Institution's work, including the setting aside of special rooms for the library, Council and Committees. The structural alterations necessary, however, will not immediately permit the building of a lecture theatre large enough to accommodate even the average attendance of 100 members at the Institution's London Section meetings.

The General Council wish to express their thanks to the Institution of Structural Engineers for their courtesy in permitting the temporary arrangement whereby the Brit.I.R.E. may use the I.Struct.E. Lecture Theatre for holding general meetings.

After December 18th, all communications for the Institution should be addressed to 9 Bedford Square, London, W.C.1. Further details regarding the new building will be given in the December issue of the Journal.

London Section Meetings

Unless otherwise stated on notices circularised beforehand, the following meetings will be held at the Institution of Structural Engineers, 11 Upper Belgrave Street, London, S.W.1 :—

The Technical Basis of Sound Reproduction.—L. E. C. Hughes, Ph.D., A.M.I.E.E. November 21st, 1942.

Modern Condenser Technique, with Special Reference to Electrolytic Condensers.—J. H. Cozens, B.Sc., A.M.I.E.E. January 23rd, 1943.

Industrial Applications of Electronics.—J. H. Reyner, A.C.G.I., B.Sc., A.M.I.E.E. February 19th, 1943.

The Functions and Properties of Accusto-Electric Transducers.—L. C. Pocock, A.M.I.E.E. March 26th, 1943.

Selective Methods in Radio Reception.—E. L. Gardiner, B.Sc. April 29th, 1943.

Cathode Coupling and Decoupled Amplifiers.—S. Hill, A.M.I.E.E. May 28th, 1943.

Graduateship Examination

The results of the May 1942 Examination are given on page 67. The November Graduateship Examination is being held in London and other principal centres throughout Great Britain; and in Alexandria, Cairo, Madras, and Bombay overseas.

The next Graduateship Examination will take place on May 14th and 15th, 1943.

The attention of members, especially registered students, is drawn to the revised syllabus and regulations of examination, now available from the Secretary. Apart from revisions in the syllabus of examination, certain amendments and alterations have been made in the list of alternative examinations recognised for the purpose of obtaining exemption.

Copies of papers set in the May and November, 1942, examinations may be obtained from the offices of the Institution, price 2s. 6d. per set, post free.

Radio Servicing Certificate Examination

Although distinct from the Brit.I.R.E. Graduateship Examination, i.e., *not* qualifying for membership of the Institution, the Radio Servicing Certificate Examination has also been held in May and November of this year.

The object of enabling the service-man to obtain proof of ability and knowledge is, of course, a service to both manufacturers and retailers. The Council has, therefore, felt that the Institution's efforts in this connection would be materially assisted by the direct co-operation of manufacturers and retailers. In order to promote this co-operation, the Council have proposed the formation of a Radio Trades Examination Board with the Radio Manufacturers' Association, the Radio & Television Retailers' Association, the Scottish Radio Retailers' Association and the Institution as contributing bodies.

Each Association and the Institution has now agreed to nominate three representatives, and commencing from the May, 1943, Examination, the Radio Servicing Certificate Examination will be conducted by the Board, who will also authorise the issue of certificates to successful candidates.

The examination will continue to comprise a three-hour written paper and a three-hour practical test. It is hoped to be able to issue a detailed syllabus of the examination, as approved by the Board, early in the New Year.

Students Section

It is proposed to hold two meetings for Students and Graduates in February and May, 1943. Details will be circulated to Registered Students and Graduate members, and the meetings will probably be held at 9 Bedford Square, London, W.C.1.

North-Eastern Section

Members in the north-eastern area have made a proposal to the General Council that a section be formed and regular meetings held in the winter months. Members and registered students interested in forming the section should communicate with the General Secretary and, in the case of Corporate Members, should indicate whether they are prepared to accept nomination for election to the local Committee.

Suggestions of subjects for discussion at meetings and papers to be read before the section will be welcomed by the Programme Committee.

British Red Cross Society

As announced in the March/May *Journal*, the Institution is despatching to prisoners of war, through the British Red Cross Society, text books and instruction material in Physics and Mathematics.

These courses and books are of value to prisoners of war who are preparing for the Institution's examination, and we have learned from member prisoners of war that classes in Radio Engineering and Servicing are being run by our members. The Institution will, therefore, appreciate any donations which members care to make for the despatch of text books and courses through the Red Cross Society.

Textbooks and instruction material in Radio Engineering proper cannot be despatched to prisoners of war as the German censorship have refused to relax their rule in this respect. The classes being run will, however, be aided by material in Physics and Mathematics.

Regulations Governing Election

The Regulations governing membership, which, with the exception of registration of student members, provide for success in, or exemption from, the Graduateship Examination, have recently been revised.

The Regulations clearly indicate the qualifications required of an applicant for election to membership, in addition to qualification by examination. Registered students and members seeking transfer to a higher grade of membership should obtain a copy of the revised Regulations before lodging a proposal form.

A copy of the Regulations with the appropriate forms of proposal and application will, of course, be sent to any applicant recommended by a member of the Institution.

THE NORTHERN POLYTECHNIC,
HOLLOWAY ROAD, N.7.

DEPARTMENT OF RADIO TECHNOLOGY

Head of Department :

S. A. HURREN, M.C., F.Brit.I.R.E.

SENIOR RADIO SCHOOL. The senior courses are intended for students who desire to qualify for technical positions in radio and television work. They are planned to include two years full-time study, after which the student may remain for individual research. Full preparation is given for the Graduateship Examination of the Brit.I.R.E., and for the appropriate examinations of the City and Guilds of London Institute.

JUNIOR RADIO SCHOOL. Full-time tuition is given in all matters relating to the elementary branches of radio technology, the third year being arranged as an intensive practical course. On completion of the junior course, students may continue their training in the senior school. L.C.C. Intermediate Scholarships and Senior Technical Awards from the Home Counties are awarded annually to the best students for this purpose.

Prospectus free on application to Secretary.

THE POLYTECHNIC
REGENT STREET, LONDON, W.I

SCHOOL OF ENGINEERING

Head of School : PHILIP KEMP, M.Sc.Tech., M.I.E.E., A.I.Mech.E.

RADIO ENGINEERING

A FULL-TIME DAY COURSE in telecommunications, extending over a period of three years, preparing for all recognised examinations and for the radio and telephone industries. School re-opens on August 31st, 1942.

EVENING CLASSES in these subjects commence on September 21st. Enrolment from 14th to 16th September, 6 to 8 p.m.

Further particulars may be obtained on application to the Director of Education

World Radio History

The Baynard Press

THE JOURNAL OF

The British Institution of Radio Engineers

PRINCIPAL CONTENTS

Vol. 3 - 3 **1942 – 43**

DECEMBER, 1942—JANUARY, 1943

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		91			9100			910000
100	100	100	10000	10000	10000	1.0 Meg.	1.0 Meg.	1.0 Meg
		110			11000			1.1 Meg
	120	120		12000	12000		1.2 Meg.	1.2 Meg.
		130			13000			1.3 Meg.
150	150	150	15000	15000	15000	1.5 Meg.	1.5 Meg.	1.5 Meg.
		160			16000			1.6 Meg.
	180	180		18000	18000		1.8 Meg.	1.8 Meg
		200			20000			2.0 Meg
220	220	220	22000	22000	22000	2.2 Meg.	2.2 Meg.	2.2 Meg
		240			24000			2.4 Meg.
	270	270		27000	27000		2.7 Meg.	2.7 Meg.
		300			30000			3.0 Meg.
330	330	330	33000	33000	33000	3.3 Meg.	3.3 Meg.	3.3 Meg.
		360			36000			3.6 Meg.
	390	390		39000	39000		3.9 Meg.	3.9 Meg.
		430			43000			4.3 Meg.
470	470	470	47000	47000	47000	4.7 Meg.	4.7 Meg.	4.7 Meg.
		510			51000			5.1 Meg.
	560	560		56000	56000		5.6 Meg.	5.6 Meg.
		620			62000			6.2 Meg.
680	680	680	68000	68000	68000	6.8 Meg.	6.8 Meg.	6.8 Meg.
		750			75000			7.5 Meg.
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		910			91000			9.1 Meg.
						10.0 Meg.	10.0 Meg.	10.0 Meg.

★ See note (1) in Text

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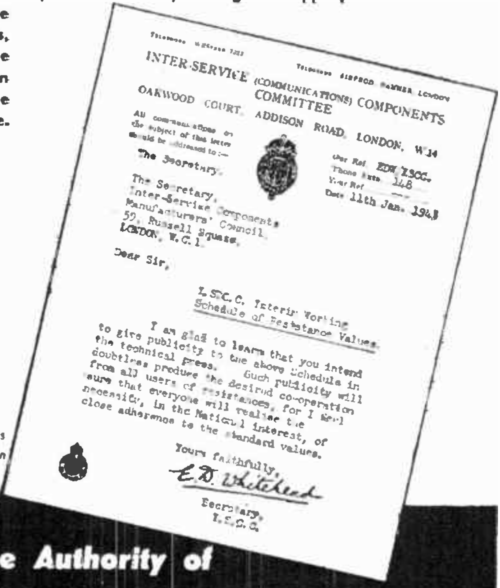

INTER-SERVICE (COMMUNICATIONS) COMPONENTS COMMITTEE
OAKWOOD COURT, ADDISON ROAD, LONDON, W.14

All communications on the subject of this letter should be addressed to:—
The Secretary.

Our Ref. EDW/I.S.C.C.
Phone Extn. 148
Your Ref. —
Date 11th Jan. 1943

The Secretary,
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Manufacturers' Council,
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Dear Sir,

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I am glad to learn that you intend to give publicity to the above Schedule in the technical press. Such publicity will doubtless produce the desired co-operation from all users of resistances, for I feel sure that everyone will realise the necessity, in the National interest, of close adherence to the standard values.

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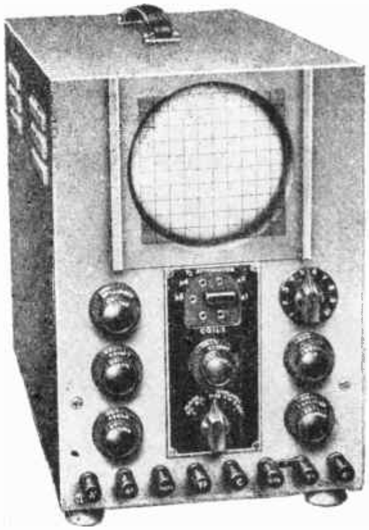

The

British Institution of Radio Engineers

(Founded 1925 Incorporated 1932)

LONDON, ENGLAND

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1942-43

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The
British Institution of Radio Engineers

9 BEDFORD SQUARE,
London, W.C.1

Vol. 3. No. 3. 1942-43 DECEMBER, 1942/JANUARY, 1943

The Institution's New Building

The leasing of new administrative offices at 9 Bedford Square, London, W.C.1, briefly announced in the last issue of the *Journal*, marks a new step forward in the progress of the Institution.

For some time, the Council had realised that, apart from other considerations, the existing offices at Duke Street House were becoming quite inadequate for the requirements of the Institution, which has considerably increased in membership since those offices were first acquired. This increase in membership, and the expansion in our activities, has necessitated an augmented staff and additional office space for the housing of files, records and reference matter.

Choice of the Building

In selecting a building suitable for the Institution's growing requirements, the Council was actuated by a desire firstly to obtain sufficient space for our present needs, with a surplus which could be employed for an anticipated expansion during the next few years ; secondly, to ensure that the internal amenities would be such as to enhance the efficiency of our administration and also to provide improved facilities for members who visit the offices to consult text books and references ; thirdly, to ensure that the situation of the building would be in a quiet neighbourhood, free from commercialism and ideally placed for the headquarters of a professional institution.

In selecting 9 Bedford Square from a number of alternatives, the Council believes that it has secured a building which satisfies all the foregoing requirements, and members who have already visited the new offices have expressed complete satisfaction with them.

Accommodation Available

The whole of the building has been leased from the Crown, and the accommodation includes the following : On the ground floor there is a large and airy general office which houses the general staff, receptionist and telephonist, and a library and reading room with adequate space for a considerable increase in the number of the Institution's text books, reference books and bound volumes of various radio journals and proceedings. The room will seat upwards of a dozen readers at a time, if need be.

The first floor comprises, firstly, a spacious oak-panelled Council Chamber and Examination Hall, in which, in future, the Institution's examinations will be held in London ; and, secondly, the General Secretary's office, a large room in which the administrative work and general direction of the Institution's activities are carried out.

The second floor contains a complete suite of offices which at the moment is vacant, but which will be used in the future to provide for expansion in the Institution's activities.

The third floor has been converted into a self-contained flat for the resident caretakers.

In the basement there is a machine room housing the addressograph and records machines, dictaphone machines, etc., and a number of other rooms which, at a later date, may be converted into research and development laboratories, as the Council may decide. Although the building is, like the remainder of those in Bedford Square, a fairly old one, it has been well modernised internally, and has central heating throughout.

The garden overlooks part of the grounds of the British Museum, and also gives a clear view of the new University of London buildings.

Historical Details

The Bedford Square estate was planned and built during the reign of King George III (1760-1820). There are original Adam fireplaces in our new headquarters, but the two main ceilings, of unusual artistic design, are the work of Thomas Leverton, who designed most of the houses and lived at No. 13 until his death in 1824.

One of the first residents at 9 Bedford Square was the Earl of Eldon, Lord Chancellor of England. His Lordship's tenancy was marked by the Gordon Riots (1780), when the house was besieged and stoned. The Square has known many other famous residents, although to-day, the only residential house is that occupied by the Countess of Oxford and Asquith.

No. 9 is on the East side of the Square, which is now Crown property ; the West, North and South sides remain part of the Duke of Bedford's Estate, the East side having been assigned as a development site for an extension of the British Museum during the reign of King Edward VII. About this time, Bedford Square became a popular centre for learned and public societies, and to-day, houses in the Square are occupied by The Associated Board of the Royal Schools of Music ; The Royal Agricultural Society ; Institute of Builders ; Association of Certified and Corporate Accountants ; National Council of Social Service ; National Farmers' Union ; Societies for the Promotion of Hellenic and Roman Studies ; The Architectural Association ; The Royal Numismatic Society ; The Sales Managers' Association ; The Royal Anthropological Institute ; the Offices of the French Consulate-General.

The Institution's new headquarters are within three minutes walk of Tottenham Court Road (Central and Northern London lines) and Russell Square (Piccadilly Line) Underground stations.

JOURNAL OF
The
British Institution of Radio Engineers

Vol. 3. No. 3. 1942-43 DECEMBER, 1942/JANUARY, 1943

THE INSTITUTION AND THE FUTURE OF THE RADIO PROFESSION

by

L. GRINSTEAD, M.I.E.E. (Member)†
(Chairman of the General Council)

The reason for the existence of any professional technical institution and the interpretation of its aims and purpose should be clearly in the minds of all its members.

A great deal has been written and said about the functions of, and the necessity for, a separate body such as ourselves, devoted solely to the science of radio and radio engineering. The whole field of activity of special engineering bodies has recently been well covered by Mr. Harry Jackson,[1] Vice-President of the Institution of Structural Engineers.

Commending thought to possible re-orientation of existing engineering institutions, Mr. Jackson joined issue with a suggestion that " co-operation with other engineering bodies in the furtherance of these standards are the activities best calculated to improve the social and economic status of the engineer." It is, however, a fact that useful joint efforts are already made by some professional bodies, especially in the mechanical engineering field. Substantial collaboration was evident, for example, in the marine oil-engine trials carried out by the Institution of Mechanical Engineers with the co-operation of the Institution of Naval Architects, the Institute of Marine Engineers and the Admiralty. A further example is afforded by the British Standards Institution, which was brought into being with the support of the leading engineering bodies and still receives financial help from a number of Institutions. Another effort in this direction was the co-operation of leading professional bodies in the formation of the Engineering Joint Council in 1922.

However, the reasons for the existence of independent professional bodies representing specialised applications of science are invariably evident in the declared objects of each Institution. Broadly, these

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† *Mullard Wireless Service Co., Ltd.*

are to be found under the headings (*a*) dissemination of technical knowledge, (*b*) development and application of specialised branches of science, (*c*) raising the status of the professional engineer.

Usually the attainment of these desirable objects is the province of committees of corporate members of each Institution. In order to co-ordinate the activities of such committees of the Brit. I.R.E., the Council appointed, in September, 1941, a Professional Purposes Committee, with suitable terms of reference.

As Chairman of this Committee, I have prepared a number of reports for Council who have advocated that the work of all Committees should periodically be reported in the Journal. In this paper, therefore, I should like to review the work of the standing Educational and Technical Committees and through them the future work of the Membership Committee.

The importance of the work of these Committees became evident when the Professional Purposes Committee were asked by the Council to submit observations on post-war planning—inseparable in the Committee's view from matters concerning the education of engineers. In fact, the reasons for this Institution's existence are so prominently to be found in its educational work that I propose to deal with that aspect of the subject first.

Dissemination of Knowledge

In his paper, Mr. Jackson has emphasised the work and objects of each body and it is in support of this specialised work in the educational and training fields that encouragement should be given to each body representing the individual profession. In the engineering professions, evidence of such encouragement and assistance is especially pronounced in the educational field. In collaboration with the Board of Education, the Institution of Electrical Engineers, the Institution of Naval Architects, the Institute of Builders and the Institute of Chemistry, all conduct schemes for National Certificates in their respective subjects. The Institution of Automobile Engineers, the Royal Aeronautical Society and the Institute of British Foundrymen, likewise co-operate with the Institution of Mechanical Engineers by endorsing its National Certificates where candidates have also taken their special subject, a further example of co-operation in the field of mechanical engineering.

With comprehensive curricula, it is not perhaps surprising that educational authorities have, until recently, given little attention to specialised training in the radio field. The present need, however, was well emphasised by Dr. R. L. Smith-Rose in his inaugural address as Chairman of the Wireless Section of the I.E.E. for the 1942-3 session. Dr. Smith-Rose[2] remarked that with the continued and rapid advance in radio and electrical communications technique, it is becoming all too clear that the radio engineering student of the future will have an impossible task in endeavouring to assimilate the fundamentals of his subject if this is to continue to be regarded as *a mere accessory* to a main course in physics or electrical engineering. " There must be many who, like myself," he said, " in taking up some branch of radio work twenty or more years ago, did not have a single lecture on radio communication in the course of our university education, and there are to-day many graduates entering the profession whose radio knowledge has been gleaned from a few mathematical lectures on the classical theory of electric waves. . . . I suggest that this Institution (I.E.E.) should consider using its influence with those responsible for the Science and Engineering faculties for Communications Engineering to be put on a standing equivalent to the degree courses in either Physics or Electrical Engineering at the present time."

The efforts of the Radio Manufacturers Association to secure a proper place for radio engineering in the curricula of technical institutions as outlined by Dr. Smith-Rose have already been acknowledged by our President, Sir Louis Sterling.[3] It is, therefore, opportune for me to outline the system of examination and award for a National Certificate in Radio Engineering, first proposed by the Brit.I.R.E. to the Board of Education in July, 1935, and recently discussed with the Association of Principals in Technical Institutes.

It is first of all necessary to remember that for a National Certificate the principal of a school or other local official acts as examinations officer and that due regard is given to the work done by students in the classroom, in the laboratory and at home. In no case is the entity of any approved school or college endangered by entering candidates for these examinations ; on the contrary, by insisting on a high national standard the scheme is intended to foster local *esprit de corps* and bring to the many centres throughout the country privileges which have hitherto been restricted to a few. The approved colleges do not find their activities curtailed in any way, but rather receive the benefits resulting from contact with the appropriate Institution, and the scheme is, therefore, an incentive for students to follow co-ordinated courses of instruction, rather than to attend isolated classes. In the case of National Mechanical Certificates, many students now follow these courses for six or seven years, or even longer, obtaining endorsements in additional subjects, including those concerned with Workshop Organisation and Management. The standard of the Higher National Certificate is that of an engineering degree in individual subjects. A student who has gained this certificate is allowed a considerable measure of exemption from the Graduateship Examination of the appropriate Institution, and in some cases is deemed to have satisfied all the Institution's educational requirements.

Such a scheme as this with, of course, radio engineering as the main subject and not as a subsidiary subject, is advocated by the Institution. Endorsements in additional subjects would provide for specialised work on some of the diverse problems now encountered in the radio field.

Development and Application of Science

All other developments in applied science have demonstrated the importance of an independent society which encourages free discussion of current technical problems. That this fact is appreciated in radio manufacturing circles is demonstrated by the fact that the Institution has recently received generous donations from radio manufacturers. Full and detailed acknowledgment of these donations will be given later, and on behalf of the Institution I take this opportunity of thanking manufacturers who have supported the Institution by donating to its funds.

In recent correspondence published in *Nature* vigorous comment is made on the unwillingness of some industrialists to permit publication or reading of papers dealing with researches carried out by their staffs. One correspondent ascribes the vigour and progress of American industry very largely to the wealth of information which is available in American literature of applied science.

No one can, of course, quarrel with the present-day need for exercising every care in publishing technical information in which there might be risk of presenting valuable hints to the enemy—far better that no information be given at all.

Nevertheless, despite *Nature's* correspondents, the Institution has found that on the whole British radio manufacturers do give encouragement to their staff to prepare papers to be read before the Institution, and that proper safeguards are taken is evidenced by the fact that of all the papers offered to the various sections of the Institution since the outbreak of hostilities only one had to be withheld for security reasons.

I believe, however, that more can be done, particularly in peacetime, towards stimulating research and development by publishing and discussing papers written by members of the Institution. In case there are members who are apprehensive from the competitive point of view, I should like to quote from a recent letter published from Dr. N. R. Campbell, of the G.E.C. Research Laboratory[4] : " What a manufacturer usually would like to learn from his competitors is not simply how to do something, but the way of doing it that has been found the best. The method most scientifically interesting is by no means always the most commercially effective. By publishing scientific work that indicates some new alternative a manufacturer does not disclose the method he is actually using."

In my view, it is essential to the success of all sections of the Institution that papers should frequently be read by members of the Institution. In encouragement of this work, the Programme and Editorial Committees have recently produced some advice and instructions for prospective readers or writers of papers, and a copy of these notes is being circulated with this issue of the *Journal.*

It is desirable that the Journal should contain a complete record of all advances in radio and electronic science and engineering and all information of use to the profession, without undue recapitulation, and mere description of well-known plant, apparatus or processes. Through the meetings regularly held in the various sections of the Institution valuable contributions can be made to the development of our profession, and I hope that as a result of the notes circulated many more members will offer to deliver papers.

Development of the Institution and the Membership Committee

A problem of the Membership Committee which is very closely concerned with post-war planning is the fact that, even now, there are a number of men who, having received some war-time mechanical training, find themselves attracted towards radio engineering.

The Committee feel that upon demobilisation of these men provision should be made to select only those who evince aptitude for radio matters and who can properly be trained and given employment in the profession. Those who are obviously unsuitable and appear incapable of being trained should not be permitted to waste their time or their war gratuities or savings on training which is unlikely to result in profitable and useful employment.

The Committee commend a suggestion made elsewhere that a Selection Board should be established at each chief demobilisation centre in order to assist ex-Service men who are not returning to definite employment or who have out-grown their pre-war job. Such a Board should preferably include representatives of specific trades or industries.

It is suggested that well-established radio manufacturers might render assistance in the form of training for suitable candidates who will later qualify for appointments on engineering or research staffs.

Apart from this aspect of new applications for membership, there are, of course, many opportunities for the development of the Institution by its attraction to (*a*) those already established in the profession and qualified or able to pass the Institution's Graduateship Examination, and (*b*) new entrants into the profession who are already engaged upon studies in preparation for the Graduateship Examination.

It is very encouraging to note the very large number of original members of the Institution who have retained their membership because, apart from the obvious privileges, including that of attending meetings, thereby mixing with men of similar occupation and interests, they realise that a professional institution exists for the general good of the profession as well as of the individual, and that it deserves, and indeed demands, the support, financial as well as moral, of each and every one of them. It is their privilege and pleasure to associate themselves with a movement which is representing their professional interests, raising its status whilst educating its younger members, and hence qualifying them for a useful career. They are the men, already respected in the profession, whose names add strength and substance to membership of the Institution and from whom its officers are mainly elected.

Then there are the members whose interests may be more directly personal ; men to whom the services of the Institution are essential, in so far as the proceedings and meetings form a post-Graduate course, whilst the opportunity for intercourse with senior members of the Institution and profession provide important contacts which are necessary for the full development and application of the individual's technical resources.

Lastly, there are the still younger members, the men who represent the profession of to-morrow, the probationers who have studied and by their studies secured entry into the profession. These men need more than anyone the friendly hand to help them forward and someone to speak for them and represent their interests.

Every profession has its recognised organisation, and it is through these Institutions or Societies that the rights of the profession are represented in official quarters and matters affecting its interests, both present and future, are watched and safeguarded.

When the war is over there will be keener competition than ever for the markets of the world, and the firms most successful in capturing those markets will be those who have had sufficient foresight to attract trained men who will develop and engineer manufacture of the right products.

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The
British Institution of Radio Engineers

THE THEORY OF UNITS

by

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A paper read before the London Section of the Institution, at the Federation of British Industries, London, on October 23rd, 1942.

Summary

In the formulation of electromagnetic theory there are four stages at which arbitrary constants are conveniently introduced for the purpose of defining units. It is customary to assign immediately the value unity to certain of these constants, after which they are lost sight of and have often at a later stage to be painfully resuscitated. In the present treatment a sketch of electromagnetic theory is given in which the suppression of these fundamental constants (k_1, k_2, k_3, k_4) does not occur. Maxwell's theory is shown to lead to a certain relationship between the k's involving the velocity of light. Subject to this and to one other restriction, the assignment of k-values is an arbitrary matter, the process of formulating a unit system being one of two degrees of freedom.

A table is constructed showing the assignment of k-values corresponding to the various known unit systems. This table can, amongst other things, be used to derive the numerical relationships between the unit quantities of the various systems. One necessary example of this is given, but it is pointed out that the (advocated) use of a generalised system of units (k's unspecified) eliminates once and for all the tiresome and inelegant process of unit changing. Moreover, this generalised system of units is free of the dimensional inconsistencies which characterise the known systems, at least in their more usual modes of expression.

Examples are given of the direct use of the generalised system of units ; a particular problem which would normally present the most tiresome process of unit changing is solved straight out in generalised units from which the numerical answers are written down at once in practical units.

Serious inconsistencies of method and nomenclature in connection with the practical system of units are brought to light and proposals for rationalisation are considered.

Introduction

The rather large number of unit systems in current use, and the consequent necessity of changing from one set of units to another, has always been something in the nature of a bugbear in the study of electromagnetic theory. Unit questions have been under discussion by various international committees over a long period, and recently the adoption of the so-called M.K.O.S. system has been advocated and actually scheduled for adoption

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in January, 1940. The long period over which the discussion has extended, and the occasionally heated correspondence which has been associated with it, are evidence that these recommendations are not wholely acceptable to engineers and physicists.

The present treatment of the subject, which is in the nature of a generalisation, aims at a somewhat radical change of the situation. Whereas the unit question has previously been an apparently unavoidable nuisance, it is now made a framework about which the whole subject is expounded and clarified.

This paper is divided into four parts :—Part 1 is a brief mathematical introduction, which has the object of introducing a small amount of original notation, and a larger amount of standard notation, which is, however, on account of a much deplored hiatus in the accepted educational schedules, largely unfamiliar to engineers. All of this notation is required for a concise exposition of Part 2, which is a review of the principal equations of the subject, with the non-suppression of the fundamental unit constants.

Part 3 is concerned with the construction of a table showing the assignment of k-values corresponding to the various known unit systems.

Part 4 comprises examples showing the use of generalised units in practice, and emphasises the elimination of the tiresome processes of unit changing.

Part 1. Mathematical Introduction

Consider a vector field **A**, by which we mean that a vector quantity **A** is specified (as to magnitude and direction) for every point of a certain domain. The vector quantity **A** is, in general terms, an abstract conception, but may be thought of physically as an electric or magnetic force, or as the velocity of a fluid in some hydrodynamical problem.

Consider an unclosed surface f bounded by a closed curve s drawn in the domain, the shapes of f and s being purely arbitrary. Next consider a small element of surface df and resolve **A** normally to this element, giving a component $\mathbf{A}_n$. Then form the integral of $\mathbf{A}_n df$ over the whole surface f. This integral is defined as the " flux of **A** through f " ; we write :

$$\mathit{flux}_f\,\mathbf{A} \equiv \int_f \mathbf{A}_n\,df$$

The justification for this notation is taken from the hydrodynamical example in which **A** is the velocity distribution in a moving fluid. It is clear that $\int_f \mathbf{A}_n\,df$ represents the volume rate of flow of fluid through the surface f; hence the term " flux " is directly expressive. It is, moreover, seen to introduce no confusion with the accepted use of the word flux in the magnetic sense, when we realise that what we call the magnetic flux is simply a shorthand for flux$_f$**B**, the vector **B** being the magnetic quantity called by mathematicians the " magnetic induction " and by engineers the " flux density."

However, in engineering it is customary to encounter the idea of flux through a loop rather than flux through a surface, so that a definition is required for the term flux$_s$ **A**. This definition is very simple, and is that flux$_s$ **A** $\equiv$ flux$_f$ **A**, that is to say the flux through a loop is defined as the flux through any surface bounded by the loop. But this will have a meaning only if it so happens that the flux through the surface f is independent of its shape and dependent only on the boundary.

Now consider two surfaces f_1 and f_2 bounded by the same closed curve s and suppose that

$$\mathit{flux}_{f_1}\,\mathbf{A} = \mathit{flux}_{f_2}\,\mathbf{A}$$

The surfaces f_1 and f_2 together define a closed volume, so that we can now distinguish between the inward and outward drawn normals. The above equation may now be written :

$$\mathit{eflux}_{f_1}\,\mathbf{A} = \mathit{influx}_{f_2}\,\mathbf{A},$$

or regarding f_1 and f_2 as constituting the single closed surface f,

$$\mathit{eflux}_{f}\,\mathbf{A} = 0.$$

The significance of this equation is particularly clear in the hydrodynamical example. It is the so-called equation of continuity, and expresses the fact that no fluid is created or annihilated within any closed volume.

It is fortunate that many of the vectors which occur in electromagnetic theory, and in particular the magnetic induction, satisfy this equation of continuity, so that we are able to attach a meaning to magnetic flux through a loop.

The efflux of a vector field proves to be important also when it is not a vanishing quantity. In this case one may associate with the eflux a differential quantity which occurs as follows :—If the surface f is reduced to enclose a vanishingly small volume, it will in the absence of certain discontinuities be found that the eflux becomes independent of the surface shape and dependent only on the volume enclosed. Thus we can specify an " eflux per unit volume" ; this quantity is known as the " divergence " ; for a formal definition we write :

$$\mathit{div}\,\mathbf{A} = \lim_{v \to 0} \frac{1}{v}\,\mathit{eflux}_f\,\mathbf{A}.$$

From the quantities associated with a surface integral we next turn to those associated with a line integral. We now fix attention on the closed curve s and resolve A along the element of arc ds giving a component A_s. The integral of the quantity $A_s ds$ taken once round the curve s is defined as the " circulation of A round s," and we write :

$$\mathit{circ}_s\,\mathbf{A} \equiv \int_s A_s\,ds.$$

A physical meaning can be attached to the circulation by considering A as an electric force, in which case $\mathit{circ}_s\,\mathbf{A}$ is the work done in carrying a unit charge round the circuit s.

The circulation has also a differential quantity associated with it. If s is made small enough (and hence plane), then again, in the absence of certain discontinuities, it will be found that the circulation becomes independent of the shape of s but proportional only to the area enclosed. There is, however, one other variant now to be considered, namely the orientation of the plane of the small loop. If we explore with this orientation until a maximum circulation is reached, we are then able to define a vector quantity having as magnitude this maximum circulation per unit area, and as direction that of the normal to the test plane when correspondingly oriented. This vector quantity is called the " curl " of A.

It remains to define one further conception to complete this notational introduction. Suppose that a scalar quantity V is specified for all points of a domain. Then the conception of differentiating this quantity in a particular direction will be familiar : that is to say, we arrive at the quantity $\frac{\delta V}{\delta s}$ as the result of differentiation in some particular direction. Now explore for the direction in which the rate of change is a maximum. We then define a vector quantity derived from the scalar field in which the magnitude is the rate of change of the scalar quantity, and the direction that in which the rate of change is a maximum. This vector is called the " gradient," and is written grad V.

Part 2. The Principal Relations of the Subject

We now proceed to a sketch of the principal relations of electromagnetic theory.

Commencing with electrostatics, the subject becomes quantitative with the law of inverse squares, which states that two charges q and q' separated by distance r repel with a force directly proportional to the product qq' and inversely to r^2.

We may express this law by the equation :

$$F = k_1 qq'/r^2,$$

which forms the basis of the subject of electrostatics.

Now it is usual in most accounts of the subject to proceed at once to the suppression of the proportionality constant k_1, by pointing out that choice of this constant has the effect only of defining the unit of charge ; hence it is convenient so to define this unit charge that k_1 takes the value unity, and thereafter drops out of the picture.

It is the author's thesis that this suppression of the constant k_1 is the last thing that should be done. This statement is open to interpretation both colloquially and literally. That is to say, in the author's opinion the constant k_1 should not be suppressed at all, but if it must be suppressed then let this be done at the end of the theory, not at the beginning.

We now proceed to the formulation of the usual electrostatic relations as they stand when the constant k_1 is unsuppressed. These relations are shown on the left-hand side of Table 1. Line 1 records the law of inverse squares. Line 2 expresses the conception of an electric force, namely, the force which would act on a unit test charge brought up to the vicinity. Line 2, however, expresses only the scalar aspect of the matter ; to include the complete vector picture we write Line 3.

Line 4 introduces the conception of a potential, namely a scalar quantity whose negative gradient gives the electric force. Note that no constant of proportionality occurs in this definition.

Line 5 gives the potential due to a point charge q. Line 5 is, of course, not a unique solution of equations 3 and 4, but implies the conventional discarding of an arbitrary additive constant.

The above covers all the necessary relations that are concerned with point charges in free space. We come now to another important form of charge distribution, that of the doublet or dipole. The conception here is a pair of charges q and $-q$ separated by a distance l. The distance l is then made to approach zero and q to approach infinity in such a way as to give a finite produce $q\,l$. This finite product is called the moment of the doublet and written M_e (electric moment).

It is now rather easy to establish the potential distribution of a doublet, and this is written in Line 6. Here θ is the angle between the radius vector and the axis of the doublet. A more convenient expression of Line 6 is written in Line 7, where the moment of the doublet is regarded as vector quantity.

It is to be noted that this peculiar charge distribution although punctiform possesses a definite axis.

When a doublet M_e is brought into a uniform electric field it will receive no translational force. If its axis makes an angle φ with the direction of the field, it will be subject to a torque $M_e E \sin\varphi$. Hence Line 8 of the Table, or, better, using vector notation, Line 9.

TABLE 1

(1)	$F = k_1 qq'/r^2$	$[F = k_2 mm'/r^2]$
(2)	$E = k_1 q/r^2$	
(3)	$E = - k_1 q \, grad \frac{1}{r}$	
(4)	$\mathbf{E} = - grad \, V$	$\mathbf{H} = - grad \, U$
(5)	$V = k_1 q/r$	
(6)	$V = k_1 M_e \cos\theta \,.\, /r^2$	
(7)	$V = k_1 \left(\mathbf{M} \;\, grad \frac{1}{r}\right)$	$U = k_2 \left(\mathbf{M}_m \, grad \frac{1}{r}\right)$
(8)	$T = M_e E \sin\varphi$	
(9)	$T = [\mathbf{M}_e \mathbf{E}]$	$\mathbf{T} = [\mathbf{M}_m \mathbf{H}]$
(10)	$efflux_f \, \mathbf{E} = 4\pi k_1 Q.$	
(11)	$div \, \mathbf{E} = 4\pi k_1 \rho.$	$div \, \mathbf{H} = 0$
(12)	$div \, \mathbf{E} = 4\pi k_1 (\rho - div \, \mathbf{P}_e)$	$div \, \mathbf{H} = - 4\pi k_2 \, div \, \mathbf{P}_m$
(13)	$4\pi k_1 \mathbf{D} = \mathbf{E} + 4\pi k_1 \mathbf{P}_e$	$k_3 \mathbf{B} = \mathbf{H} + 4\pi k_2 \mathbf{P}_m$
(14)	$W''' = E^2/8\pi k_1$	$W''' = H^2/8\pi k_2$
(15)	$circ \, \mathbf{H} = 4\pi \frac{k_2 k_4}{k_3} I$ (Ampère)	
(16)	$circ \, \mathbf{E} = - k_4 \dot{\Phi}$ (Faraday)	
(17)	$\frac{k_2 k_4^2}{k_1 k_3^2} = \frac{1}{c^2}$	

We now come to one of the most important theorems in the subject of electrostatics, Gauss's Theorem ; this states that the eflux of electric force through a surface enclosing a total charge Q is $4\pi k_1 Q$. (Line 10 of the Table.)

The combination of an aversion to any really expressive notation and an urge to the immediate rejection of important constants leads to a particularly objectionable but very widespread formulation of this theorem in the terms " the number of lines of force leaving a charge Q is $4\pi Q$." To attach any precise meaning to a statement such as this is beyond the mental powers of the present writer, although it is apparently expected to be easily within the grasp of our first-year students.

Averting from this disagreeable aspect of Gauss's theorem, we may turn our attention to a quick proof :—

Consider a point charge q located within the closed surface f. The normal component of electric force at the element df is $\cos\psi.\ k_1 q/r^2$. Hence for the point charge q,

$$\mathit{eflux}_f\,\mathrm{E} = \int_f \cos\psi.\ k_1 \frac{q}{r^2}\,df = \int k_1 q\, d\Omega = 4\pi\, k_1 q.$$

Thus a point charge q contributes an eflux $4\pi k_1 q$ irrespective of its position within the surface; hence the gross charge Q, made up of any distribution of point charges $q_1, q_2 \ldots\ldots q_n$, contributes $4\pi k_1$ Q.

Application of Gauss's Theorem to a distributed charge leads naturally to:

$$\mathit{div}\,\mathrm{E} = 4\pi k_1\, \rho.$$

This (Line 11 of the Table), coupled with Line 4, is the familiar Poisson's Equation.

All the above refers to distributions of charges in free space. When dielectrics are present we have a new situation to deal with. The behaviour of a dielectric is expressed by saying that in the presence of an electric field it becomes subject to an electric strain, i.e. an elastic separation of positive and negative charge throughout the volume. This condition is expressed by defining a distributed vector, termed the Polarisation $\mathbf{P}_e$, this being the electric moment per unit volume. It is found (Poisson's Transformation) that a distribution of Polarisation $\mathbf{P}_e$ contributes a spurious charge distribution $-\mathit{div}\,\mathbf{P}_e$.

In the presence of dielectrics, Line 11 becomes

$$\mathit{div}\,\mathrm{E} = 4\pi k_1 (\rho - \mathit{div}\,\mathbf{P}_e) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(Line 12)}$$

or

$$\mathit{div}\,(\mathrm{E} + 4\pi k_1 \mathbf{P}_e) = 4\pi\, k_1\, \rho.$$

Maxwell introduced a vector which he termed the displacement, **D**, defined as the vector whose divergence is ρ. Hence we reach:

$$4\pi k_1 \mathbf{D} = \mathrm{E} + 4\pi k_1 \mathbf{P}_e \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(Line 13)}$$

as the definition of Maxwell's displacement vector in terms of the electric force and polarisation.

To complete this sketch of electrostatics, it remains only to write without proof an expression for the energy density; this is given in Line 14 of the Table.

Passing on now to Magnetism or, more strictly, to Magnetostatics, the quantitative commencement of the subject is usually made with the so-called law of inverse squares for magnetic poles. (Line 1, R.H.S. of the Table.) This, however, seems to the author a little unfortunate, since all that we know of magnetism tells us that the free magnetic pole is an entity without the possibility of physical existence.

What we encounter in magnetism is not the free pole but the dipole. It would seem, therefore, desirable for the dipole to form the basis of any analysis of the subject. The natural experimental entity in magnetism is the small compass needle. If this is viewed on a not too small scale it is seen to have the essential properties of a dipole. These properties it shows most conveniently in relation to a uniform magnetic field such as that of that of the earth, a quantity whose existence can hardly escape experimental notice. Thus we arrive quickly at

$$\dot{\mathrm{T}} = [\mathrm{M}_m\, \mathrm{H}] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(Line 9)}$$

as an expression for the torque experienced by a magnetic dipole M_m in a magnetic field H.

The magnetic field is found to have properties analogous to those of the electric field, and it is easy to fit to it a potential function U, defined by the relationship

$$H = -\,grad\,U \quad \ldots\ldots\ldots\ldots\ldots\ldots\text{(Line 4)}$$

Finally, when we come to examine the field of the dipole itself we reach experimentally

$$U = k_2\left(M_m\,grad\,\frac{1}{r}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\text{(Line 7)}$$

Thus, of the first 9 electrical relations the table we are able rationally to fill in only 3 magnetic analogies, Lines 9, 4 and 7. Lines 1, 3 and 5 have physically no magnetic analogies; nevertheless the law of inverse squares for magnetostatics has a certain mathematical meaning, and is allowed to appear (in brackets) on the R.H.S. of the table, Line 1.

Following on to write in as many analogies as possible, we have for free space

$$div\,H = 0, \quad \ldots\ldots\ldots\ldots\ldots\ldots\text{(Line 11)}$$

since the non-existence of free magnetic unipolar matter implies $\rho_m = 0$.

If, however, we depart from free space and examine conditions within magnetisable substances, which are the magnetic analogies of dielectrics, we are led at once to the conception of a magnetic polarisation vector P_m (Note 1) expressing the magnetic moment per unit volume. Again we find by Poisson's transformation that a distribution of polarisation P_m gives rise to a fictitious distribution of free magnetic charge given by

$$\rho_m = -\,div\,P_m \quad \ldots\ldots\ldots\ldots\ldots\ldots\text{(Note 2)}$$

Thus we reach

$$div\;H = -\,4\pi k_2\,div\,P_m \quad \ldots\ldots\ldots\ldots\ldots\ldots\text{(Line 12)}$$

as expressing conditions in the presence of magnetisable substances. Hence, in these circumstances, the vector $H+4\pi k_2\,P_m$ has a zero divergence. This vector is called by Maxwell the "magnetic induction," B, and we write with Maxwell

$$B = H + 4\pi k_2\,P_m$$

We are, of course, at liberty to adopt a different definition for the magnetic induction, provided that we handle it appropriately. We might, for instance, write

$$4\pi k_2\,B = H + 4\pi k_2\,P_m$$

This definition would have considerable advantages in addition to being fully analogous to the electrical side. (Note 3.) So far as is known, no writer has as yet adopted this definition. On the other hand, a number of writers, in particular the Giorgi School, assume as their definition of B,

$$k_2\,B = H + 4\pi k_2\,P_m$$

Note 1.—P_m is written for the more usual notation I ("intensity of magnetisation"), in order to avoid a clash with the symbol for current.

Note 2.—The full expression of Poisson's transformation is that a distribution of polarisation P is equivalent to a volume distribution given by the negative divergence of the polarisation, plus a surface distribution given by the discontinuity of the normal component of polarisation at any transition surface. For the sake of simplicity the latter term has been omitted in the above description, since it can be considered as a limiting case of the former.

It appears then, that there is a diversity of opinion as to what constant should be associated with the magnetic induction vector in formulating its definition. In order to achieve complete generality we will here specify this constant arbitrarily by introducing a new constant k_3 and write

$$k_3 \mathrm{B} = \mathrm{H} + 4\pi k_2 \mathrm{P}_m \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad \text{(Line 13)}$$

Again, to complete this survey of magnetostatics it remains to write, without proof, an expression for the energy density ; this is given in Line 14, R.H.S. of the Table.

The above covers the principal equations of the separate subjects of electrostatics and magnetostatics ; the question now arises, in what way do these two subjects correlate ? The answer to this is that so long as the subjects remain static they do not correleate at all ; that it is only when we come to the dynamical aspects of the matter that any correlation appears. The work of elucidating this correlation was performed by Faraday and Ampere, who thereby created the whole of the electrical industry.

The first step in establishing this correlation is the identification of "current" of voltaic electricity with rate of transport of "charge" of electrostatics. It is then noted that this current has certain magnetic properties. One convenient expression of the magnetic behaviour of a current is to state that a current loop behaves like a uniform magnetic shell, whose shape may be any surface bounded by the current loop, and whose shell strength (magnetic moment per unit area) is proportional to the current. Thus, we may write for the equivalent shell strength.

$$\tau = k_5 \mathrm{I}$$

and for the magnetic potential

$$\mathrm{U} = k_2 \tau \Omega = k_2 k_5 \mathrm{I} \Omega .$$

The above equation implies that for any two field-points P_1 and P_2,

$$\int_{\mathrm{P}_1}^{\mathrm{P}_2} \mathrm{H}_s \, ds = \mathrm{U}_2 - \mathrm{U}_1 = k_2 k_5 \mathrm{I} (\Omega_2 - \Omega_1).$$

Now consider the path $\mathrm{P}_1 \mathrm{P}_2$ to be extended into a closed curve (P_2 coinciding with P_1). The equation now becomes

$$circ_s \, \mathrm{H} = k_2 k_5 \mathrm{I} . \triangle \Omega .$$

$\triangle \Omega$, the difference in solid angle at the beginning and end of the path, will be zero for any path which does not cut the current, but will have the value 4π for a path which does cut the current.

Thus the circulation of magnetic force round a closed path is $4\pi k_2 k_5$ times the current through it, and we write

$$circ \, \mathrm{H} = 4\pi k_2 k_5 \mathrm{I} .$$

This is Ampere's circuital relation.

Now suppose that we have any arbitrary distribution of permanent magnetism defined by a polarisation vector P_m. By use of Poisson's Transformation this may be represented by a fictitious distribution of free magnetism

$$\rho_m = - \, div \, \mathrm{P}_m .$$

Note 3.—For instance the energy density becomes $\int (\mathrm{H} \, d\mathrm{B})$, which is a very desirable relation if B is to be regarded as the "displacement" corresponding to a "force" H.

The mutual potential energy of the current and the magnetic system is then

$$\int_v \rho_m \, \mathrm{U} \, dv$$

$$= \int_v \rho_m \, k_2 \, k_5 \, \mathrm{I} \, \Omega \, dv$$

$$= k_5 \, \mathrm{I} \, flux_s \, \mathrm{H}$$

$$= k_3 \, k_5 \, \mathrm{I} \, flux_s \, \mathrm{B}$$

$$= k_3 \, k_5 \, \mathrm{I} \, \Phi$$

Now suppose that the current is allowed to do work on the magnetic system by moving it about. The rate of doing work is clearly $- k_3 \, k_5 \, \mathrm{I} \, \dot{\Phi}$. But the only way in which a current can do work is by association with an E.M.F. This E.M.F. is, in our notation $circ_s \, \mathrm{E}$.

Thus $$\mathrm{I} \, circ_s \, \mathrm{E} = - k_3 \, k_5 \, \mathrm{I} \, \dot{\Phi},$$

or $$circ_s \, \mathrm{E} = - k_3 \, k_5 \, \dot{\Phi} \quad \text{.................. (Note 4)}$$

This is Faraday's circuital relation.

It is now convenient to replace the constant $k_3 \, k_5$ by the single constant k_4, whereupon the circuital relations of Ampere and Faraday become as given in Lines (15) and (16) of the Table.

These two circuital relations form the usual basis for the development of electromagnetic theory. It should be noted that they are not independent ; either can be derived from the other or from any other statement of the correlation between the subjects of electrostatics and magnetostatics, there being only one independent correlation.

The constant k_4 now introduced is rather different in nature from the previous constants ; whereas these have been arbitrarily assigned, in the case of k_4, when values have been assigned to the previous constants, the value of k_4 is a quantity fixed by Nature and awaiting measurement. Faraday and Ampere performed this measurement.

However, the value of the constant k_4 can not only be measured but can also be calculated. This work was performed by Maxwell, who thereby founded the industry of radio, no less certainly than did Faraday and Ampere the more general electrical industry.

The notation adopted in this account of the subject is ideally suited to a brief exposition of Maxwell's Theory, which will now be given.

We commence by writing the circuital relations of Faraday and Ampere in differential form, viz. : $$curl \, \mathrm{E} = - k_4 \, \dot{\mathrm{B}}$$

$$curl \, \mathrm{H} = 4\pi \frac{k_2 k_4}{k_3} \, \mathbf{i}$$

Here $\mathbf{i}$ is the vectorial current density.

Note 4.—The fact that the circuital relations have here emerged with their correct conventional signs is fortuitous. The important point is that considerations, somewhat on the line of Lens' law, lead to the conclusion that if a consistent scheme is applied for the sense in which the circulation is reckoned, the two circuital relation must have opposite signs ; as to which of them should carry the negative sign is a matter of convention. The accepted scheme is consistent with a "right-handed" vector convention.

Now applying these equations to free space, we have:

$$curl\, \mathbf{E} = -\frac{k_4}{k_3}\dot{\mathbf{H}}$$

$$curl\, \mathbf{H} = 4\pi\frac{k_2k_4}{k_3}\dot{\mathbf{D}}$$

$$= \frac{k_2k_4}{k_1k_3}\dot{\mathbf{E}}$$

This last equation has expressed Maxwell's idea of a displacement current: his theory is that to obtain the total effective current density at any point we must add to the conduction current density the rate of change of the displacement vector.

These two equations are now very symmetrical. Eliminating one of the variables, say **H**, we have

$$curl\, curl\, \mathbf{E} = -\frac{k_4}{k_3}\, curl\, \dot{\mathbf{H}}$$

$$= -\frac{k_4}{k_3}\frac{\delta}{\delta t}\, curl\, \mathbf{H}$$

$$= -\frac{k_4}{k_3}\frac{\delta}{\delta t}\cdot\frac{k_2k_4}{k_1k_3}\dot{\mathbf{E}}$$

$$= -\frac{k_2k_4^2}{k_1k_3^2}\ddot{\mathbf{E}}$$

But from a general theorem of vector analysis we have:

$$curl\, curl\, \mathbf{E} = grad\, div\, \mathbf{E} - \nabla^2\mathbf{E}$$

and, since $div\, \mathbf{E} = 0$ in free space, $grad\, div\, \mathbf{E}$ vanishes.

Hence finally $\nabla^2\mathbf{E} = \frac{k_2k_4^2}{k_1k_3^2}\ddot{\mathbf{E}}$

and likewise $\nabla^2\mathbf{H} = \frac{k_2k_4^2}{k_1k_3^2}\ddot{\mathbf{H}}$

These equations tell us that **E** and **H** are propagated through space with a velocity u given by

$$\frac{1}{u^2} = \frac{k_2k_4^2}{k_1k_3^2}$$

Maxwell made the bold assumption that light was an electromagnetic phenomenon, and concluded that this velocity u was none other than the known velocity of light c.

Part 3. The Unit Systems

It will now be seen that the process of formulating a unit system amounts primarily to the assignment of values to the constants k_1, k_2, k_3, k_4. This assignment must be subject to Maxwell's "Restriction":

$$\frac{k_2k_4^2}{k_1k_3^2} = \frac{1}{c^2}$$

Otherwise the assignment is arbitrary, except for the fact that there would be no sense in assigning unrestricted values to the constant k_3; this constant can reasonably assume only one of three values:—

$k_3 = 1$ (Maxwell)
$k_3 = k_2$ (Giorgi)
$k_3 = 4\pi k_2$

Thus the assignment of the *k's* is a process having two degrees of freedom.

Secondly, it is of course necessary to specify a set of mechanical units to which the system shall refer.

Table 2 is a formulation of most of the known unit systems. The first three lines are concerned with systems based on the centimetre-gramme-second (c.g.s.) system of mechanical units. For our purposes, however, we shall refer to this as the centimetre-dyne-second (c.d.s.) system, since *force* enters more directly into electrical relations than does *mass*.

TABLE 2

	System	Mechanical Units			k_1	k_2	k_3	k_4
		L	F	T				
(1)	Electrostatic	cm	dyne	sec	1	$1/c^2$	1	1
(2)	Electromagnetic	cm	dyne	sec	c^2	1	1	1
(3)	Gaussian	cm	dyne	sec	1	1	1	$1/c$
(4)	Heaviside—Lorentz	cm	dyne	sec	$1/4\pi$	$1/4\pi$	1	$1/c$
(5)	Practical	cm	dyne	sec	$10^{-2}c^2$	—	—	—
(6)	Practical	cm	10^7 dyne	sec	$10^{-9}c^2$	10^{-9}	1	1
(7)	Practical	cm	10^7 dyne	sec	$10^{-9}c^2$	10^7	1	10^{-9}
(8)	Practical	m	10^5 dyne	sec	$10^{-7}c'^2$	10^{-7}	1	1
(9)	Practical (Giorgi)	m	10^5 dyne	sec	$10^{-7}c'^2$	10^7	k_2	1
(10)	Practical (Modified Giorgi)	m	10 dyne-	sec	$10^{-7}c'^2$	$\frac{1}{16\pi^2} \cdot 10^7$	$4\pi k_2$	1
(11)	Practical (Quadrant)	10^7 m.	10^{-2} dyne	sec	c''^2	1	1	1

The natural step is now to assign unit values to certain of the constants, and in these three systems k_3 is taken a dimensionless constant of value of unity. It is thus possible to make any two of the other three constants unity ; the remaining constant then takes its value as given by Maxwell's Restriction.

Line 1 is the familiar Electrostatic system. Based on the law of inverse squares for electrostatics, k_1 is naturally made unity ; k_4 is the second choice for unity value, and k_2 accordingly takes the value $1/c^2$.

Line 2 is the Electromagnetic system. Here k_2 is the primary choice for unity value, k_4 is the second choice, and k_1 takes the value of c^2.

There is only one other possibility ; this is to take k_1 and k_2 each as unity, leaving k_4 to take the value $1/c$. This is the " Gaussian " system.

Line 4 expresses the so-called Heaviside-Lorentz system. The object here is to eliminate the recurrence of the quantity 4π in the principal relations of the subject. This is achieved by choosing $k_1 = k_2 = 1/4\pi$, k_3 still remains at 1, and k_4 takes the value $1/c$.

This suppression of the quantity 4π is called by Heaviside " rationalisation." The system of Line (4) is thus a " rationalised " Gaussian system.

Although the rationalised system of Heaviside-Lorentz is very much used in theoretical writings, the author has some doubts as to its ultimate value. The situation may be described somewhat frivolously by saying that the quantity 4π satisfies an equation of continuity on its own account ; it cannot be eliminated or created, but only moved about from one place to another. This entertainment would seem to be an elaboration of the old-fashioned pastime known as " squaring the circle."

Before passing on to the Practical system of units, the elucidation of which is the most important function of Table 2, we may pause to reflect that if we are prepared to depart from accepted units of length, the choice is open to us to assign mechanical units in which the velocity of light appears as unity. Such a choice would allow us to assign unity values to all of the constants k_1, k_2, k_3 and k_4 simultaneously. This system would appear to have some merit for theoretical purposes, at least according to one line of thought. It is, however, inconsistent with the author's viewpoint, which is that the escritorial advantage of eliminating the basic constants is outweighed by the clarification of ideas which results from their deliberate retention.

Coming now to the Practical system, we are accustomed to the idea that the Practical units are quasi-arbitrary multiples of the c.d.s. electromagnetic units. In fact only one numerical relationship is required, the simplest being that connecting the units of charge, viz. that the Practical unit of charge, the Coulomb, is one-tenth of the c.d.s. electromagnetic unit. Thus constructing Line (5) from Line (2) of the Table, we specify $k_1 = 10^{-2} c^2$. We must, however, proceed no further along this line because the Practical system, referring, as it does, to the mechanical units Joule and Watt, will not allow itself to be expressed on a basis of c.d.s. mechanical units. The Joule and the Watt belong properly to the m.K.s. (metre-kilogramme-second) system. This system is, however, not unique in possessing the Joule and Watt as its units of work and power. Any system possessing the second as its unit of time will do equally well provided that its units of length and force are consistent with the Joule as unit of work. Thus, if we wish to retain the centimetre as unit of length, which from many points of view is convenient, we merely have to stipulate that the unit of force is to be 10^7 dynes.

This brings us to Line (6) of the Table, which expresses the Practical system in relation to this cm-10^7 dyne—sec system of mechanical units. k_1 becomes $10^{-9} c^2$, this value being derived from that immediately above by taking account of the new force unit. k_3 and k_4 each remain unity so that k_2 takes the value 10^{-9}.

These four simple entries in Line 6 of the Table, together with the statement of the mechanical units, completely specify the Practical system. In a sense, indeed, they specify it rather too completely, since they cast the limelight on what amounts to an engineering malpractice. This point turns on a matter of nomenclature which will now be described.

As soon as the subject of Electromagnetism began to show signs of a technological development, the necessity of having names allotted to the various units must have been apparent. There were some ten quantities requiring names, six of these being electrical, and four magnetic. As, however, there are no less than five unit systems, we are basically confronted with the task of providing 50 names. Such a procedure is clearly out of the question, so that the very reasonable decision seems to have been reached that all units should remain anonymous other than those of the Practical system.

Accordingly the following names were assigned :—

Charge	Coulomb
Current	Ampere
Potential	Volt
Resistance	Ohm
Inductance	Henry
Capacitance	Farad
Magnetic potential or M.M.F.	Gilbert
Magnetic force	Oersted
Magnetic induction or flux density	Gauss
Magnetic flux	Maxwell

With regard to the first six of these units, the author has no quarrel. As to the last four, it has to be pointed out that these units are not those of the Practical system at all, but those of the c.d.s. electromagnetic system. According to any rational scheme, these c.d.s. units are not eligible for naming at all.

What, then, are the true magnetic units of the Practical system? As far as the author is aware only one such has been named. This is the unit of magnetic flux and is called the Weber.

We may now use Table 2 to determine the relation between the Weber and the corresponding c.d.s. electromagnetic unit, the Maxwell. This example will also serve to illustrate the use of the Table for conversion purposes. The first step in performing a conversion is to form the " dimensions " of the quantity concerned. In the case of flux we reason as follows :—

From Table 1, Line 1, right-hand side, we can write the dimensions of magnetic pole strength as

$$m = F^{\frac{1}{2}}\, L\, k_2^{-\frac{1}{2}}$$

$$\text{Thus}\quad H = F^{\frac{1}{2}}\, L^{-1}\, k_2^{\frac{1}{2}}$$

$$B = F^{\frac{1}{2}}\, L^{-1}\, k_2^{\frac{1}{2}}\, k_3^{-1}$$

$$\phi = F^{\frac{1}{2}}\, L\, k_2^{\frac{1}{2}}\, k_3^{-1}.$$

Next we note that for a quantity whose dimensional product contains only positive indices of F, L, T, k_1, k_2 .. k_n, the size of the unit increases with increase of the units of F, L. T, and with the numerical decrease of the k's (Note 5).

$$\text{Thus}\quad 1\ \text{Weber} = 10^{\frac{7}{2}}\ .\ 1.\ 10^{\frac{9}{2}}.\ 1.\ \text{Maxwells}$$

$$\text{or}\quad 1\ \text{Weber} = 10^{8}\ \text{Maxwells}.$$

We recognise this number as one of the irritants in transformer and generator design. This number would not occur in engineering formulæ if flux were correctly reckoned, that is to say in Webers instead of in Maxwells.

Whilst the wrongful christening of the c.d.s. magnetic units in place of the legitimate Practical units constitutes the main anomaly of the Practical system, there are some other misfortunes which are worth recording. The first is that Maxwell's name should have been chosen as one of a group whose composition is out of line with Maxwell's thought. The point referred to here is the co-existence of separate units for magnetic force and magnetic

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Note 5.—This statement contains the essence of the principle which Lanchester terms " the Freshman's Springe."

induction, viz. the Oersted and the Gauss. According to Maxwell's definition these quantities are co-dimensional and should not require (or indeed tolerate) separate units. It is only when we come to the non-Maxwellian definition of the magnetic induction that separate units are admissible.

Possibly engineers have sensed the impropriety of the situation, since they steadfastly refuse to use the term Maxwell, clinging fanatically to their mystic term "line."

Again, the christening of the magnetic quantities appears to have caused affront to the traditional fairy godmother. Thus, in connection with the naming of the single genuine Practical magnetic unit, the Weber, the curse has fallen in the choice of an initial letter which clashes with that of Watt, so that a foul occurs in the systemised scheme of notational abbreviation. (See Appendix.)

We pass now to Line (7) of the Table, which is an expression of the mixed Practical system in current engineering use. Owing to the rather hideous mixture of unit conceptions involved and to the record of awkward numbers appearing, the author is tempted to call this the "Unpractical system." Yet, this system duly comprises all the ten named quantities listed above. The only quantities which take unfamiliar values are the magnetic pole and dipole. Since the latter occurs seldom in engineering, and the former never, this is not a matter of great importance. The only respect in which it is out of line with current nomenclature is that here the Oersted and the Gauss become synonymous (since $k_3 = 1$ numerically and dimensionally).

In Line 8 we rewrite Line 6 of the Table, but with reference to the m.K.s. system of mechanical units ; i.e. in our notation, the metre—10^5 dyne—sec system. Note that the symbol c' is now written for the velocity of light in order to emphasise that it differs numerically from the value previously used, viz. :

$$c = 3 \times 10^{10} \text{ cm/sec.}$$

$$c' = 3 \times 10^{8} \text{ metres/sec.}$$

This system is a valid presentation of the Practical system in reference to m.K.s. mechanical units, but has some unfamiliar magnetic units, viz. :

Flux	Weber
Flux density and magnetic force	Weber per square metre
Magnetic potential or M.M.F.	Weber per metre

Line 9 presents the so-called M.K.O.S. or Giorgi system, and differs from Line 8 in the choice of the constant k_3, which is here taken as numerically and dimensionally equal to k_2. The magnetic units in the Giorgi system are :—

Flux	Weber
Flux density	Weber per square metre
Magnetic force	$1/4\pi$ Ampere per metre
M.M.F.	$1/4\pi$ Ampere

Line 10 is an "ultra-rationalised" Giorgi system. The term is used, with some diffidence, to distinguish it from rationalising in the Heaviside-Lorentz sense. In common with all of these presentations of the Practical system the electrical quantities are the normal named items, Ampere, Volt, etc.

Note 6.—Assuming, at least, that the author has correctly read the Giorgi system, which is not altogether an easy matter.

The magnetic quantities, however, in this case are considerably unfamiliar, viz. :—

Flux	$16\pi^2$ Weber
Flux density	$16\pi^2$ Weber per square metre
Magnetic force	Ampere per metre
M.M.F.	Ampere

In comparison with the Giorgi system (Note 6), this latter system seems to have a good deal to recommend it. A christening of the new flux unit is required to complete the system. The author feels, however, that the introduction of any new unit or system is inexpedient.

There is yet one other representation of the Practical system which it seems necessary to mention. This is a scheme described by Maxwell and termed by Lanchester the " Quadrant system." In this system the mechanical units are so chosen that the Practical electrical units become an absolute (Maxwellian) electromagnetic system referred to these. This system is shown in Line 11 of the Table. The mechanical unit choice which effects this system is that of the unit of length at 10^7 metres, or one Earth's quadrant—hence Lanchester's terminology.

Part 4. Conclusions and Examples

The above has shown some of the points of confusion which exist in connection with the Practical System of Units. It may be thought that to present the Practical System in six different forms is not to clarify the matter but only to leave " confusion worse confounded." The author is certainly not prepared to point to any one of these presentations as having the outstanding balance of advantage ; indeed, to do so would be inconsistent with his point of view, which, as already suggested, is that the most useful procedure is to work always in *general units* up to the final stage of numerical evaluation. The particular system which accepts the problem in its own stated units and gives the answer in the required units is then selected, and the numerical answer obtained by writing in the appropriate values for the *k*'s.

This procedure will now be illustrated by some concluding examples.

Example 1.—Find the capacity of the Earth in microfarads :—

The point of this question, which is taken from an old Mathematical Tripos (Note 7), is that no explicit data whatever is given, all the necessary data residing in unit definitions.

The intended form of solution was presumably as follows :

Let r_o be the radius of the Earth in cms. Then its capacity is r_o (E.S.U.).

$$= \frac{1}{9 \times 10^{11}} r_o \text{ farads.}$$

But, by definition of the metre,

$$\frac{1}{2} \pi r_o = 10^7 \text{ metres} = 10^9 \text{ cms}$$

Hence $$C = \frac{1}{9 \times 10^{11}} \cdot \frac{2}{\pi} \cdot 10^9 \text{ farads.}$$

$$= 706 \text{ microfarads.}$$

Note 7.—The author has not yet been able to find the date of this Tripos, but considers that he has now discovered what is meant by the expression " The Golden Age."

According to the present method we write (using Line 5 of Table 1):

$$C = \frac{1}{k_1} r_o$$

$$\frac{1}{2} \pi r_o = 10^7 \text{ metres}$$

$$C = \frac{1}{k_1} \cdot \frac{2}{\pi} \cdot 10^7$$

In order to obtain C in farads with the metre as unit of length, we use any of the systems of Lines, 8, 9 or 10, Table 2, for which

$$k_1 = 10^{-7} c'^2 = 9 \times 10^9$$

$$\text{Thus } C = \frac{1}{9 \times 10^9} \cdot \frac{2}{\pi} \cdot 10^7 \text{ farads}$$

$$= 706 \text{ microfarads.}$$

The distinction between the two solutions is here one of style rather than of convenience; the problem being so simple that no serious inconvenience arises in any case. In the latter version, however, we have been saved the step of making the dimensionally questionable statement that the capacity of a sphere is equal to its radius in centimetres.

Example 2.—Derive Child's equation for the temperature-saturated plane diode :—

The problem is to determine the potential and electron-velocity distributions in the plane diode assuming that electrons are emitted freely with zero initial velocity; thence to obtain the relation between anode voltage and current per unit area.

Let x denote distance normally from cathode, the anode being the plane $x = a$. Equations to be satisfied are :—

1. Poisson's Equation. $\nabla^2 V = -4\pi k_1 \rho$,

$$\text{or in this case } \frac{d^2V}{dx^2} = -4\pi k_1 \rho.$$

2. The hydrodynamical equation of continuity

$$div\,(\rho \mathbf{u}) = o;$$

$$\text{in this case } \frac{d}{dx}(\rho u) = o$$

$$\text{or } \rho u = -I$$

3. The dynamical equation

$$m\,(\mathbf{u}\, grad)\,\mathbf{u} = e\, grad\, V$$

$$\text{Here, then, } m\left(u \frac{du}{dx}\right) = e \frac{dV}{dx}$$

$$\text{or } \frac{1}{2} mu^2 = eV$$

Eliminating the variables ρ and u we write

$$\frac{d^2v}{dx^2} = 4\pi k_1 \ \frac{I}{u} = 4\pi k_1 I . \left(\frac{2e}{m}\right)^{-\frac{1}{2}} V^{-\frac{1}{2}}$$

Integrating, $$\left(\frac{dV}{dx}\right)^2 = 4\pi k_1 I \left(\frac{2e}{m}\right)^{-\frac{1}{2}} 4 \, V^{\frac{1}{2}}$$

$$\frac{dV}{dx} = \left(16\pi \, k_1 I\right)^{\frac{1}{2}} \left(\frac{2e}{m}\right)^{-\frac{1}{4}} V^{\frac{1}{4}}$$

$$\frac{4}{3} \ V^{\frac{3}{4}} = \left(16\pi \, k_1 I\right)^{\frac{1}{2}} \left(\frac{2e}{m}\right)^{-\frac{1}{4}} x$$

$$V = \left(\frac{3}{4}\right)^{\frac{4}{3}} \left(16\pi \, k_1 I\right)^{\frac{2}{3}} \left(\frac{2e}{m}\right)^{-\frac{1}{3}} x^{\frac{4}{3}}$$

$$V_a = \left(\frac{3}{4}\right)^{\frac{4}{3}} \left(16\pi \, k_1 I\right)^{\frac{2}{3}} \left(\frac{2e}{m}\right)^{-\frac{1}{3}} a^{\frac{4}{3}}$$

Whence, $$I = \left(\frac{3}{4}\right)^{-2} \left(16\pi k_1\right)^{-1} \left(\frac{2e}{m}\right)^{\frac{1}{2}} a^{-2} \, V_a^{\frac{3}{2}}$$

For the numerical computation we select the system of Line 6 of Table 2, thus reaching directly the current density in amps per square cm, while V is reckoned in volts and anode-cathode separation in cms.

There is only one point which is at all tricky : this is that e/m must be reckoned in Coulombs per 10^7 grammes, and thus takes the value $1{\cdot}76 \times 10^{15}$.

$$\text{Thus } I = \left(\frac{3}{4}\right)^{-2} \left(16\pi \, . \, 9 \times 10^{11}\right)^{-1} \left(3{\cdot}52 \times 10^{15}\right)^{\frac{1}{2}} a^{-2} \, V^{\frac{3}{2}}$$

$$= 1{\cdot}78 \cdot \frac{1}{144\pi} \cdot 10^{-11} \left(35{\cdot}2\right)^{\frac{1}{2}} \cdot 10^{7} \cdot a^{-2} \, V^{\frac{3}{2}}$$

$$= 2{\cdot}33 \times 10^{-6} \quad a^{-2} \quad V^{\frac{3}{2}} .$$

Example 3.—Find the electric and magnetic field strengths corresponding to a plane-wave radiation intensity of 1 watt per square metre.

We know that intensity of radiation is expressed by the Poynting vector $k_6\,[\mathrm{EH}]$. In order to add interest to this example, we will assume that the constant of proportionality k_6 is not known, and commence with a Lemma showing how this constant may be obtained.

Lemma

We know from Table I that the electric and magnetic energy densities are respectively $\dfrac{E^2}{8\pi k_1}$ and $\dfrac{H^2}{8\pi k_2}$.

Hence, we may consider that in a plane wave the energy travels with a velocity given by

$$\frac{k_6 \, EH}{\dfrac{E^2}{8\pi k_1} + \dfrac{H^2}{8\pi k_2}}$$

Considering this as a function of the two (scalar) variables E and H, we find that this is the maximum when

$$\frac{E}{\sqrt{k_1}} = \frac{H}{\sqrt{k_2}}$$

This maximum velocity can safely be assumed to be that of light, whence

$$\frac{k_6 \mathrm{E}^2 \sqrt{\frac{k_2}{k_1}}}{\left(\frac{\mathrm{E}^2}{4\pi k_1}\right)} = 4\pi k_6 \sqrt{k_1 k_2} = c$$

or

$$k_6 = \frac{c}{4\pi \sqrt{k_1 k_2}}$$

The intensity of radiation for a plane wave can thus be written

$$\begin{aligned} \mathrm{W}'' &= \frac{c}{4\pi \sqrt{k_1 k_2}} \mathrm{E\,H} \\ &= \frac{c}{4\pi k_1} \mathrm{E}^2 \\ &= \frac{c}{4\pi k_2} \mathrm{H}^2 . \end{aligned}$$

Now for the numerical evaluation.

Since the problem is set with the metre as the unit of length, we may conveniently select one of Lines 8, 9 or 10 of Table 2 ; let us choose Line 8.

For E we have

$$\begin{aligned} & \sqrt{\frac{4\pi k_1}{c'} \mathrm{W}''} && \text{Volts per metre} \\ &= \sqrt{4\pi \,.\, 10^{-7} c'} \;\sqrt{\mathrm{W}''} && \text{Volts per metre} \\ &= \sqrt{120\pi} \;\sqrt{\mathrm{W}''} && \text{Volts per metre} \\ &= 19{\cdot}4 && \text{Volts per metre} \end{aligned}$$

For H we have

$$\begin{aligned} & \sqrt{\frac{4\pi k_2}{c'} \mathrm{W}''} && \text{Webers per square metre} \\ &= \sqrt{\frac{4\pi\, 10^{-7}}{c'}} \;\sqrt{\mathrm{W}''} && \text{Webers per square metre} \\ &= \sqrt{\frac{4\pi}{3} 10^{-15}} \;\sqrt{\mathrm{W}''} && \text{Webers per square metre} \\ &= \sqrt{41{\cdot}8 \cdot 10^{-8}} \;\sqrt{\mathrm{W}''} && \text{Webers per square metre} \\ &= 6{\cdot}46 \,.\, 10^{-8} && \text{Webers per square metre} \end{aligned}$$

Owing to our non-familiarity with the Weber as a unit, we have, in order to get a physical appreciation of this magnitude, to take a somewhat retrograde step and express this in Oersteds or Gauss, these units being synonymous in the system of Line 8.

We have then

$$\begin{aligned} \mathrm{H} &= 6{\cdot}46 \times 10^{-8}. && \text{Webers per square metre} \\ &= 6{\cdot}46 && \text{Maxwells per square metre} \\ &= 6{\cdot}46 \times 10^{-4} && \text{Maxwells per square cm.,} \\ & && \text{Oersteds, or Gauss.} \end{aligned}$$

If one's object in making this calculation is the very proper one of obtaining a quantitative grip on the "go" of radiation, one may notice that both these field-strengths are rather small compared with everyday quantities, e.g. the static fields of the earth, viz. 300 volts per metre and 0·20 Oersted, approximately. (Note 8.)

This is in spite of the fact that at an intensity of 1 watt per square metre the field strength is what we should commonly describe as overpowering, being that corresponding to spherical radiation of a *megawatt* at a range of 282 metres.

If, on the other hand, one's interest is more general than numerical, one may note in this example some points of considerable physical significance. The first is that the equations relating the electric and magnetic fields with the radiation intensity are, somewhat surprisingly, independent of frequency. Secondly, we derived above the equation

$$E = \sqrt{120\pi} \quad \sqrt{W''}$$

$$\text{or } W'' = E^2/120\pi$$

Here E is the field strength in volts per metre, and W″ the power intensity in watts per square metre.

Comparing this with $W=V^2/Z$, the formula for the power supplied to an infinite line of characteristic impedance Z fed with a voltage V, we note that this quantity 120π (ohms) can be regarded as the characteristic impedance of space.

If one examines the nature of the quotient E/H, one finds that only with the system of Line 10 does this quantity properly emerge as 120π ohms, again the characteristic impedance of space.

This quantity is of importance in connection with a subject whose treatment is classical, but whose importance is modern, that of Wave Guides.

Note 8.—The author is indebted to a colleague. Mr. M. L. Jofeh, for pointing out this representation of the magnitudes. Also for an alternative solution to Example 3, which checks the figures here given.

Acknowledgments and References

This presentation of the Unit Systems by means of a table of *k*-values is an elaboration of a scheme given by the late T. I'a Bromwich as an introduction to the subject of Electromagnetic Waves.

Ths following references are given :—

(1) *Practical Absolute System of Electrical Units.* (Phys. Soc. Proc. 48, 445, 1936.) Report on Electrical and Magnetic Units to the International Conference on Physics.

(2) F. W. Lanchester. *Electrical Dimensions and Units.* Paper read before Section G of the British Association at Blackpool, September, 1936. (Reprinted, with discussion, in "Engineering," September, 1936—February, 1937.)

(3) F. W. Lanchester. *The Theory of Dimensions and its Application for Engineers.* (1937.)

APPENDIX

Since the author holds very strong views on the importance of correct and systematic notation, he ventures to give here his interpretation of the accepted scheme of notational abbreviation.

All named units are represented by a single initial letter. If the unit is a proper name the initial is a capital, viz., A, V, W, for Ampere, Volt, Watt. If the unit is not a proper name, the initial is a small letter ; thus m, g, s, for metre, gramme, second. There is only one partial exception to this scheme ; Ohm gives in an unfortunate initial letter, and is therefore Hellenised ; but note Ω, not ω.

Next, there are assigned the following prefixes to denote multiples by powers of 10 :—

10^6	10^3	10^{-1}	10^{-2}	10^{-3}	10^{-6}	10^{-12}
M	K	d	c	m	μ	p
(Mega)	(Kilo)	(deci)	(centi)	(milli)	(micro)	(picro)

The unit symbols follow directly on the associated numeric without the inclusion of any stops, hyphens or strokes ; the first and last of these signs being reserved to denote products and quotients respectively.

The following, then, are examples of correct notation ; beside them are written some incorrect notations which are unfortunately encountered rather frequently :—

Quantity	*Correct Notation*	*Incorrect Notation*
2 milliamps	2 mA	2 M/A. 2M/a
10 megohms	10 MΩ	10 megΩ, 10Ω
10 kilohms	10 KΩ	10 TΩ
100 microvolts	100 μV	100 μ/V
50 microvolts per metre	50 μV/m	50 μv/m
20 decibels	20 dB	20 db
5 kilometres	5 Km	5 km
1·77 microhm cms.	1·77 μΩ.cm.	1·77 μΩ/cm^3
Insulation figure for condenser type	1000s	1000 MΩ/μF

The following examples for interpretation have been compiled as a rather searching test on one's comprehension of the scheme :—

Ky, KG, μM, μm, mb, MD.

Exception has been taken to some of these, but the author considers that only the third is at all open to question ; this is because a capital M reads the same in English as in Greek ; this example might therefore denote either a flux of one micromaxwell or a conductance of one micromho.

DISCUSSION

Dr. L. E. C. Hughes :

" This tabulated method is very helpful. There was considerable discussion before the war as to the acceptance of Giorgi's system by the Electrical Board, and Mr. Bedford's paper clears up many of the difficulties of the M.K.S. system."

Mr. Mynall :

" This is an admirable set of tables, and I would like to see others made up. There should be a parallel between E and H, and D and B ; also between

D and H, and E and B. The 4π factors introduce themselves naturally, but they can be taken out again."

" Mr. Bedford is inconsistent in condemning the use of the free magnetic pole, but then using it himself to derive Ampere's circuital relation."

Mr. A. T. B. Bardens (Associate Member) :

With regard to the use of c, this is passed over as being 3×10^{10} cms./sec. The value is actually under investigation at the moment but is about $2{\cdot}9775 \times 10^{10}$ cms./sec. We have to stick to that value.

" In 1935 it was decided that the M.K.S. system should be adopted, but no decision was reached on the 4π. It was a pity that it was not decided to rationalise the units at the same time."

Mr. M. Levy (Associate Member) :

" Concerning 4π ; in a system in which this is suppressed, can one use the normal Practical units ? "

Mr. E. K. Sandeman :

" I personally find no difficulty in working in one set of units and then multiplying by suitable factors to convert to another set. Mr. Bedford has to do much the same thing with his constants k. Where then is the advantage of the k method ? "

Mr. J. A. Sargrove (Member) :

In the above criticism the speaker can be likened to the critics of the decimal system. The advantage of Mr. Bedford's method is that there is one set of constants less to remember. The advantage lies in the one with the smallest number of constants. The seventh power of 10 occurs in Mr. Bedford's paper three times, and is thus rather easy to remember."

Mr. R. Benjamin (Student member) :

" Has any system of units ever been proposed which is based only on fundamental natural constants, such as the charge of an electron, the mass of a proton, Planck's constant, the universal gratitional constant and the velocity of light? Such a system would naturally bring about enormous simplifications in numerous formulæ and calculations. To mention only one example, the introduction of the velocity of light as unit velocity would make the electrostatic and electromagnetically derived units equal to one another.

" Obviously, any three of the above natural units could be used (instead of three arbitrary units of distance, mass and time) and would be sufficient to base upon them all units that can be based on the c.g.s. system (including also heat and temperature units, when derived thermodynamically), with the advantages hinted above. A disadvantage would be that the numbers encountered would often be inconveniently large or small, unless suitable decadic multiples or sub-multiples are used."

Mr. H. A. Hartley (Member) :

" The point of the Heaviside system is to put 4π into its place. Matters would not be upset by adopting Mr. Bedford's thesis, but we should get rid of 4π if we can."

Mr. A. Wynn :

" Mr. Benjamin's suggestion seems to be very complicated. Choosing the units to make $c = 1$ would make things easy from one point of view only. However, the units we use must fit into the world as we know it. The mechanical units which hold the Joule as unit of work and make the velocity of light unity are 3×10^8 metres, $\frac{1}{3} \times 10^{-3}$ dyne, and the second. These units do not fulfil this condition. Compromise is reached in the M.K.S. system.

REPLY TO THE DISCUSSION

I should be very sorry if Dr. Hughes has interpreted my remarks as an advocation of the Giorgi system. My point of view will perhaps be clear from the written paper, if it was not from my condensed reading of it.

Mr. Mynall will notice that I have met his criticism of inconsistency in condemning the magnetic pole and then using it. The procedure adopted in the read version of the paper was forced on me only by pressure of time.

Mr. Barden's point is of interest, but belongs more to an aspect of the subject which I have not touched, that of fixing accurately the basic numerical standards.

Mr. Levy touches the spot. As far as I can see, rationalisation in the Heaviside-Lorentz sense knocks the bottom out of the Giorgi system, in producing units which are not the familiar named items.

Mr. Sandeman's point is, I think, answered by my examples, which I was unable to give fully in the reading of the paper. If he is still unconvinced, then our ideas on style must be very different.

I am glad to note that Mr. Sargrove is in agreement with my point of view on this matter.

Mr. Benjamin is, I think, largely answered by Mr. Wynne. Perhaps I may add that since our ideas of measurement are now so firmly established and the apparatus for measurement (rules and meters) installed on such a vast scale, any attempt to " shatter them to bits and then remould them nearer to the heart's desire " appears to be out of the question.

Mr. Hartley concerns himself with the matter of 4π, a question which appears to me to have received an excess of attention. My views on this are given in the paper, but I would add that I have occasionally adopted an artifice to save writing this 4π, which yet avoids losing it ; this is to write k' for $4\pi k$.

The

British Institution of Radio Engineers

NOTICES

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Gifts to the Institution's Library

The General Council acknowledges with thanks donations of books and proceedings from Mr. A. L. Beedle (Fellow), Messrs. W. B. Medlam, G. A. V. Sowter and F. E. Herzog (Members), G. Parr (Associate Member), and Mr. Sherley-Price (Student).

Books received but already duplicated in the Institution's library are sent to prisoners of war through the British Red Cross Society.

Dates of Forthcoming Meetings

Unless otherwise stated on notices circularised beforehand, the following meetings will be held at the Institution of Structural Engineers, 11 Upper Belgrave Street, London, S.W.1 :—

Industrial Applications of Electronics.—J. H. Reyner, A.C.G.I., B.Sc., A.M.I.E.E. February 19th, 1943, at 6.15 p.m.

Selective Methods in Radio Reception.—E. L. Gardiner, B.Sc., March 26th, 1943, at 6.30 p.m.

The Functions and Properties of Acousto-Electric Transducers.—L. C. Pocock, A.M.I.E.E. April 29th, 1943, at 6.30 p.m.

Cathode Coupling and Decoupled Amplifiers.—S. Hill, A.M.I.E.E. May 28th, 1943, at 6.30 p.m.

Annual General Meeting.—Friday, September 3rd, 1943, at 6.30 p.m.

North-Eastern Section

Mr. H. Armstrong (Associate Member) has kindly undertaken the organisation of future meetings of the North-Eastern Section, and members in this section who wish to assist in its development should communicate with Mr. Armstrong at 44 Osborne Road, Jesmond, Newcastle-on-Tyne.

November Graduateship Examination Results

The Examination and Education Commitee will publish the results of the last Graduateship Examination on January 30th. Recommendations will also be made to the General Council for the award of the following prizes to the most successful candidates in the examinations held during 1942 :—

1. The President's Prize.
2. The Mountbatten Medal.
3. The L. R. C. Prize.

The
British Institution of Radio Engineers

NOTES ON R.F. ATTENUATOR DESIGN

by

R. E. Blakey, D.Sc., Ph.D.†

A paper read before the North-Western Section of the Institution, at the College of Technology, Manchester, on October 17th, 1942.

Functions of Networks of the Attenuating Type

This paper is concerned with attenuating networks employing resistive elements. The unit of resistance is the ohm, which constitutes the Primary standard in electrical units. Determination of the ohm in terms of absolute value can be made to an accuracy of one part in 10 million (*vide* Curtis, Bureau of Standards, Washington). It is most unlikely that constructors of attenuating networks will determine each element embodied therein to such a degree of accuracy. Convenience dictates that lower degrees of accuracy should be accepted, hence each resistive element is likely to be determined in terms of comparison with other elements of known accuracy; *e.g.*, Wheatstone's Bridge for moderate values of resistance, and Kelvin's Bridge for low values of resistance. Potentiometric methods may also be employed. By such devices and employing refined methods, it is possible to determine the value of each resistive element to an accuracy of one part in 10,000, or even a few parts in 100,000. A combination of numerous resistive elements inevitably causes further errors, so that the overall accuracy is likely to be of the order of one part in 1,000, or a few parts in 10,000.

An attenuating network is required to serve as a potential divider. How accurately it fulfils this function depends largely on the degree of precision to which we determine its elements. From the foregoing it would appear that we may expect potential division to an accuracy of one part in 1,000. This is comparable with the degree of accuracy possible with a "workshop pattern" D.C. potentiometer. In the case of the D.C. potentiometer, the standard of potential difference is almost certainly a Weston cadmium cell, a device of high accuracy. However, it is most unfortunate that a comparable standard is non-existent for standards of potential difference for alternating current conditions, and even more so for high frequency current conditions.

Therefore, we are strictly limited in our work by the appreciable degrees of uncertainty arising from the lack of standards of high frequency current and for potential difference. As will be seen from the later sections of this paper, the accuracy of resistance determination at high frequencies is, by comparison with the D.C. case, of a low order.

I therefore suggest that we should regard such "guesswork calibrations" as appear on signal generators as travesties of the truth. Indeed, the precise sub-division of 1 volt D.C. into steps of 1 μV is especially difficult to achieve with any real degree of precision, and the problem at 1 Mc/s is enormously more complex. With a realisation of the nature of the problems before us, I propose to deal with the basic calculations, forgetting for the moment the

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† *Salford Electrical Instruments, Ltd.*

" impurities " which, as will be seen later, greatly affect the simple conception of attenuation networks.

Basic Calculations for Ladder Networks

Fig. 1 (*a*) illustrates a typical ladder network in which the first four sections are shown and an infinite number of additional sections should be imagined to follow.

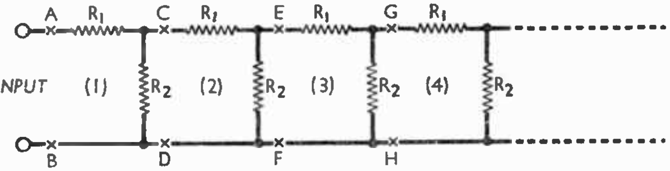

Fig. 1 (a).

The input resistance as measured at AB can be represented by a single resistance R (Fig. 1(*b*)). R is defined as the characteristic resistance of the network. If the first section be removed, the new input resistance as measured at CD will also be R. Hence the first section plus the remainder of the network can be represented as at Fig. 1 (*c*).

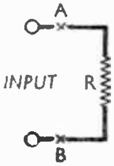

Fig. 1(b)

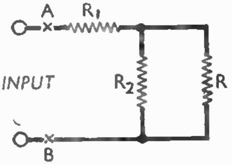

Fig. 1(c)

Let the voltage attenuation ratio of any section, *i.e.*, the voltage ratio AB/CD, CD/EF, EF/GH, etc., be denoted by A, then it follows from Fig. 1(*b*) and (*c*) that :

$$A = \frac{R - R_1}{R} \quad \dots\dots\dots\dots\dots\dots (1)$$

therefore $$R = \frac{R_1}{1 - A} \quad \dots\dots\dots\dots\dots\dots (2)$$

and $$R_1 = R\,(1 - A) \quad \dots\dots\dots\dots\dots\dots (3$$

But a further expression for A can be derived from Fig. 1(*c*) :

$$A = \frac{\dfrac{1}{\dfrac{1}{R_2} + \dfrac{1}{R}}}{R_1 + \dfrac{1}{\dfrac{1}{R_2} + \dfrac{1}{R}}}$$

$$= \frac{R\,R_2}{R\,R_1 + R_1\,R_2 + R_1R_2} \quad \dots\dots\dots\dots (4)$$

Equating (1) and (4) it will be seen that :

$$R_2 = \frac{R^2 - R\,R_1}{R_1} \quad \dots\dots\dots\dots\dots\dots (5)$$

When the network is used as an attenuator, it is common practice to apply a known voltage to the input AB and to tap off the voltage attenuated to a known extent at the points CD, EF, GH, etc. In the centre of an infinite series of sections, the resistance as measured from these tapping-points can be represented as at Fig. 1(*d*) and is seen to be :

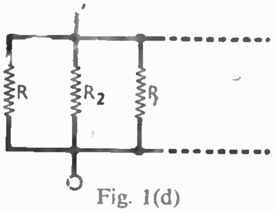

Fig. 1(d)

$$\frac{1}{\frac{1}{R_2}+\frac{1}{R}+\frac{1}{R}} = \frac{R\,R_2}{2\,R_2+R} \qquad \ldots\ldots(6)$$

A finite number of sections can be made to appear from the output terminals as an infinite series of sections by making the resistance of the source applied to the input and the resistance of the final element each equal to

$$\frac{R\,R_2}{R - R_2}$$

i.e., R_2 in parallel with R.

Network Arrangements : General Survey

Some typical arrangements are shown in Figs. 2—6. One arrangement deliberately omitted is the variable input to the potentiometer type. Such a system possesses more bad features than any other and thus is unworthy of our consideration.

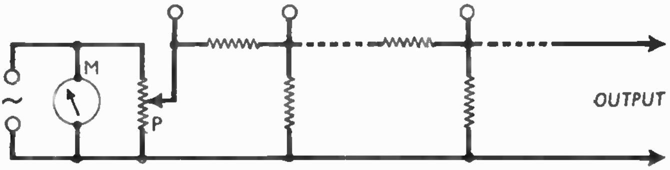

Fig. 2.

By far the most suitable arrangement is that where a constant input is applied to the network and the output controlled by fixed and variable elements in the attenuator proper. In Fig. 2 the fixed input potential as indicated by the meter M is fed to the potentiometer P, and the variable output from P is attenuated in finite steps to the rest of the following network.

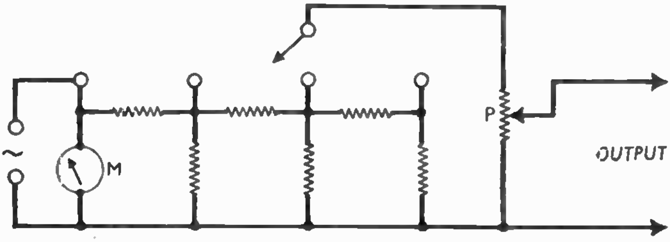

Fig. 3.

Fig. 3 shows an arrangement where the potentiometer P is in the output circuit and is connected into progressive sections of the attenuator by a switch. This arrangement is seldom used, because it does not fulfil the requirement of constant output impedance. This same objection applies also to Fig. 4, where the fixed input is switched along the ladder network.

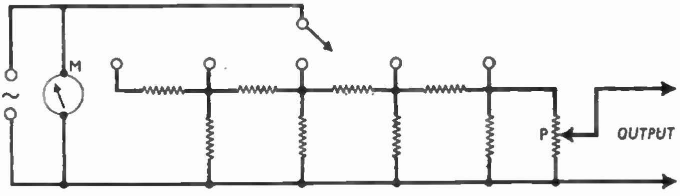

Fig. 4.

The arrangements of Figs. 2—4 have one common feature in that the potentiometer must be accurately calibrated, non-reactive, and compensated for the load into which it works. Quite obviously such collective demands are somewhat impracticable.

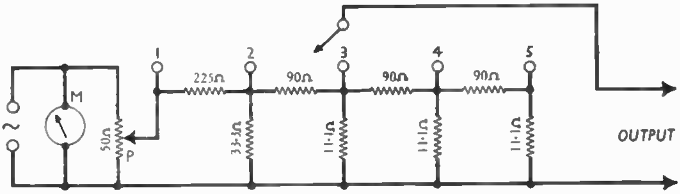

Fig. 5.
Efficient and inexpensive form of attenuator for low power signal generator.

Fig. 5 shows an arrangement which satisfies most of present day requirements. The ratio between steps is 10 : 1, thus providing a convenient multiplying factor. Following generally accepted practice, the low voltage sections have an output resistance of ≑ 10Ω, and the high voltage sections a resistance of 25Ω. Assuming an input to the potentiometer of 0·1 volt, the following range accrues :

Tap 5.	1 —	10 µV
,, 4.	10 —	100 µV
,, 3.	100 —	1,000 µV
,, 2.	1 mV —	10 mV
,, 1.	10 mV —	100 mV

The input resistance to the network proper is 250Ω, therefore P should be about 50Ω to reduce the error resulting from moving the slider up and down. The power required from the oscillator is

$$\frac{0{\cdot}1^2}{42} = 0{\cdot}00025 \text{ watt (say } 0{\cdot}25 \text{ mW)}$$

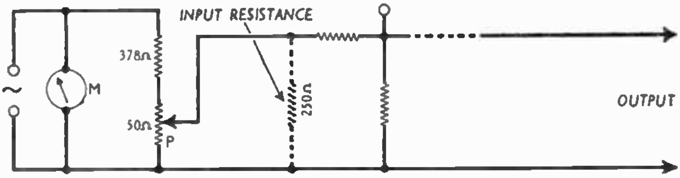

Fig. 5 (a).

Fig. 5(*a*) represents an improvement with respect to Fig. 5, in so far as the error resulting from moving the slider of P is minimised in its effect as the network proper is shunted across only a fractional part of the oscillator output. It is by no means difficult to get 1 volt output from any average oscillator, therefore by making the total load resistance equal to $(9 \times 42) + 42\Omega = 378\Omega + 42\Omega$ the voltage developed across the 42Ω effective resistance is equal to one-tenth of the whole, thus being 0·1V. It will also be seen that a logarithmic calibration of the potentiometer P is now possible. The power required from the oscillator in this case is 2·5 mW, *i.e.*, ten times that for Fig. 5.

The arrangement of Fig. 5(*a*) has much in its favour for normal work and can be well recommended. It is interesting to note that the General Radio Co. (U.S.A.), Marconi-Ekco, Ferris (U.S.A.), Siemens & Halske (Germany) use arrangements very similar to Figs. 5 or 5(*a*) in their Signal Generators.

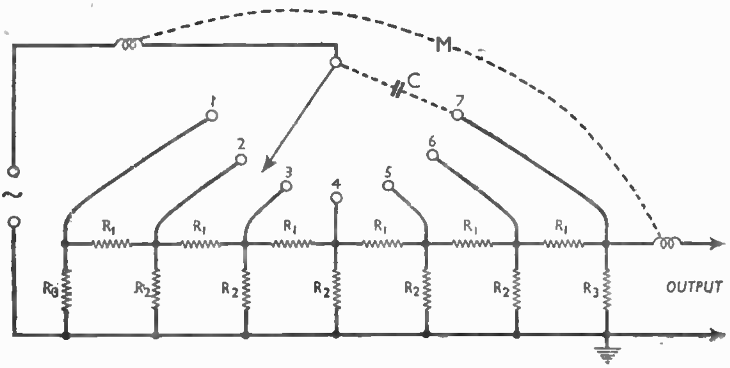

Fig. 6.

In Fig. 6 we have shown an attenuation network of the so-called " high power " type. The output impedance is 5Ω in this case, and the input power required is 200 mW for 1 V input. For purposes of simple study, the inductive elements indicated by the sign of mutual inductance M and the capacitative element C should be ignored. This type of network tends to be of rather specialised nature and is not commonly used. Nevertheless, it is very useful in those spheres where much higher degrees of accuracy are demanded than in normal radio work. Such terms are, however, well outside the scope of this paper. Commercial examples of high power attenuation networks are those by Muirhead & Co., and Dr. Dietz & Ritter G.m.b.H. (Germany), the last-named concern producing an example of outstanding merit but at a cost well outside most people's pocket.

To close this survey of common types of attenuation networks, it is desirable to point out that the " low power " types of attenuation network have currents of the order of 5 mA passing through them, whilst the " high power " type have currents of 50 mA or more passing through them.

R.F. Indicating Instruments

The input voltage to a complete network is usually 1 V or 0·1 V. Quite obviously this input potential should be as accurately known as possible, and to this end, some form of indicating instrument is needed. It is indeed unfortunate that H.F. indicating instruments do not possess any real degree of accuracy, and errors of about 10 per cent. or even more are likely in the usual radio frequency range.

Early examples of signal generators almost invariably used thermal milliammeters connected in series with the potentiometer as the indicating device. Yet if you care to measure the characteristics of a typical 5 mA thermo-couple over quite a limited frequency range, I am sure you will find such appreciable changes in effective resistance that the potentiometer and network proper could never hope to fulfil their purpose with even fair degrees of accuracy. Improvements in recent years in thermo-couple design have helped matters considerably, and now the Weston pattern can be regarded as quite satisfactory up to 20 Mc/s. However, low current patterns are not available, thus precluding the use of the improved types in low power signal generators. It is useful to note that the Muirhead high power attenuator utilises a thermo-couple input. The German firm of Hartmann & Braun produced a specialised form of high frequency ammeter similar in many respects to the design of Professor Fortescue. The German instrument was used in the Dr. Dietz & Ritter G.m.b.H. attenuator with much success.

Hot-wire instruments of the Hartmann & Braun and Johnson & Phillips type have occasionally been used, but with little success.

Present day practice is to use a valve voltmeter connected directly across the generator output, and provided that a reasonable scale deflection can be obtained for an output of 1 V, this method seems to be by far the best. Where quite high frequencies (say 20 M/cs) are envisaged, the " Acorn " type seems to be the most satisfactory arrangement.

Numerous published designs of good valve voltmeters are available, so no further comment of mine is necessary.

Electrical Design Features

Common practice is to build attenuators covering 5 or 6 decades, that is 10^5 or $10^6 : 1$, but I wish to emphasise the fallacy of assuming that because we introduce an attenuation network, having on face value an attenuation ratio of $10^6 : 1$, between a 1 V source and the load (radio receiver) we should get 1 μV applied to the load. Previous sections have dealt in general terms with typical circuits, but casual mention of errors has been made. In the preceding section, I endeavoured to show the errors which may accrue from unsatisfactory forms of indicating instruments. Important as these items are, they are, nevertheless, overshadowed by the " leakance " components which may arise in a badly designed network.

Reverting to Fig. 6 and considering now the items M and C, which we previously ignored, it is interesting to evaluate these " leakance " items in practical measure. Assume the switch to be at step 1 and the p.d. between that point and ground to be 1 V. In an error-free network the output p.d. would be 1 μV. Let us assume the highest frequency of interest is 20 Mc/s. At this frequency, the capacitance C must have a value of less than 1/500th part of a picofarad ($\mu\mu$F) if it is to cause an error of less than 100 per cent. in the output p.d. A capacitative reactance of 5 Ω at 20 Mc/s causes a " stray 1 μV " to be introduced into the output circuit. Such a value is not impossible to achieve, but the magnitude of screening demanded is indeed formidable. However, the mutual inductance between the input and output-sections is far worse.

Again taking the same switch setting, the same input voltage and the same output voltage for an error-free network, and also assume 20 Mc/s to be the highest frequency of interest as in the previous example, an inductive reactance of 5 microhms ($5 \times 10^{-6}\Omega$) permits the introduction of a " stray 1 μV " into the output circuit. Expressed in terms of mutual inductance between input and output circuits, M would have a value of 4×10^{-8} μH and cause 100 per cent. error. Whilst such a value may be obtained, the cost would be absolutely prohibitive.

Contrasting with the former case is where the input voltage to the network is 10 mV. The value of M could then be 4×10^{-6} μH—100 times greater than the former case—if a " stray 1 μV " were to be introduced into the output circuit. No doubt it will come as an unwelcome surprise to some of you to learn how such small quantities can so easily introduce such large errors. We may, therefore, write that for a given amount of " stray potential " injection into the output circuit, from the input circuit, the maximum values of both stray capacitance and stray mutual inductance vary inversely as the applied voltage and input current.

It will therefore be seen that the design of a network involves due consideration of many minute quantities if accurate results are required. The haphazard approaches so obviously made to network design have resulted in the present-day unsatisfactory state of affairs where the radio engineer is accepting values as shown on a dial but which are often far removed from the true values.

In addition to the electrical design of a complete network we must give full consideration to the design of the individual elements. In Appendices 1—3, I have gone fairly deeply into this matter and I do hope you will carefully study the mathematical treatment contained therein, as it will show once again how tiny components must be evaluated in their true proportion if success is to be assured.

Conclusions

(1) High frequency attenuation networks demand the closest possible attention to detail in both complete design and the individual element design.

(2) Stray effects (mutual inductance and capacitative coupling) must be reduced to the smallest possible values. This involves intensive screening and the avoidance of " loops " causing mutual inductance from stage to stage, and especially from input to output. The " earthing " side must be a " common-point " earth and not a " plurality of points " earth.

(3) The self inductance (L) and capacitance (C) of resistance cards must not be ignored no matter if they do appear to be small.

(4) The so-called " mica-card " winding is productive of large errors, principally due to L at 20 Mc/s. A modified form of bifilar winding is preferable, but C should be kept low.

(5) The Ayrton-Perry winding offers advantages when both L and C of the " go " and " return " wires are carefully balanced. This form of winding is limited by practical dictates to low values of resistance.

(6) The Curtis-Grover winding offers advantages, but is difficult to execute.

(7) Composition resistances are quite untrustworthy and should not be countenanced (see Marshall, Puckle, Sowerby, Howe and Boella for complete treatment).

Table 1. Comparison of Resistance Windings

Date, 1917. *Prof. Laws. Mass. Institute of Technology, U.S.A.*

Nominal Resistance of Coil (Ohms)	Eff. Inductance in μH at 1,200 c.p.s.			Change in Resistance 0—1,200 c.p.s.		
	C. & G.	L. & N.	S. & H.	C. & G.	L. & N.	S. & H.
0·1	0·005	0·14	0·18	—	—	—
1·0	0·05	0·4	0·5	—	—	—
10·0	0·3	0·9	1·0	—	—	—
100·0	−1·6	−5·0	−2·0	—	—	—
1,000·0	−16	−400	−100	< ·001	−0·08	−0·05
5,000·0	30	—	−27,500	< ·001	—	−0·2
10,000·0	100	—	−100,000	< ·001	—	−1·0

ABBREVIATIONS

C. & G. = Curtis & Grover—Special Winding.
L. & N. = Leeds & Northrup Co., Philadelphia, U.S.A.
S. & H. = Siemens & Halske, Berlin.

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For detailed winding methods see :—

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(Article Prazision Hochfrequenz messbrucke), in German, Körting Mitteilungen, Blakey. May, 1937.

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(Article, Kurzwellen Widerständ Messtechnik), in German.

The various Instrument makers have supplied data as given hereunder anent their products. The Author expresses his thanks to them all.

Table 2. Non-reactive Resistances

H. W. Sullivan, Ltd., 1938

Nominal Resistance of Coil (Ohms)	Time Constant L/R (Seconds)	Tan $\phi = \omega L/R$ at 5,000 c/s.
10,000	10^{-9}	3×10^{-5}
1,000	2×10^{-9}	5×10^{-5}
100	2×10^{-9}	5×10^{-5}
10	2×10^{-8}	5×10^{-4}
1	5×10^{-8}	$1{\cdot}5 \times 10^{-3}$
0·1	2×10^{-7}	5×10^{-3}

Table 3. R.F. Decade Resistance (1·5 Mc/s)

H. Tinsley & Co., 1941. *Type R.F.*1

Nominal Resistance of Coil (Ohms)	Mean change of Inductance for any change of dial settings μH
0·1	0·01
1·0	0·01
10	0·01
100	0·01
	Residual Inductance = 1 μH Residual Capacitance = 10$\mu\mu$F live side to screen

Table 4(a). Decade Resistances

Type 5. *Muirhead & Co.* 1942

Effective inductance (μH) at 1,000/c/s

Nominal value Ω	1	10	100 (1)	100 (2)	1,000 (1)	1,000 (2)
At Switch Setting 1	0·12	0·20	0·2	0·2	36	31
At Switch Setting 10	0·60	1·2	8	−5	530	−560

(1) Shield earthed.
(2) Shield to potential end.

Table 4(b). Percentage Error in Impedance

Type 5. *Muirhead & Co.*

Nominal value in Ohms	Switch Setting	Frequency in kilocycles per second						
		50	100	200	500	1,000	5,000	10,000
1	1	0·1	0·3	1	5	25	—	—
	5	0	0·1	0·2	1·8	7	—	—
	10	0	0	0·2	1·8	7	—	—
10	1	0	0	0	0·2	0·8	18	—
	5	0	0	0	0·2	0·6	15	—
	10	0	0	0	0·1	0·3	7	—
100	1	0	0	0	0	0	0·2	0·8
	5	0	0	0	0	0	0·2	0·8
	10	0	0	0	0	0·1	3·1	12
1,000	1	0	0	0·1	0·6	2·5	—	—
	5	0	0	0·2	1·0	4	—	—
	10	0	0	0·2	1·4	5	—	—

Table 5. Variable Attenuators 0—1 Mc/s. H. or T. Types

Siemens & Halske A.G., Berlin, 1939

Deviations from Nominal Value

Neper Steps (× 10)	0·01	0·1	1·0	1·0 at 100 Kc/s
Deviation in Nepers	≦0·0001	≦0·01	≦0·1	≦0·02

Table 6. Residual Inductance. Decade Resistance at 1,000 c/s

Cambridge Instrument Co.

Resistance (Ohms)	Residual Inductance (μH)
Zero	+0·53
1	+0·5
10 × 1	+0·79
10	+0·8
10 × 10	+0·85
100	+0·6
10 × 100	−0·5
1,000	+0·4

Table 7. Change in Impedance (as a % change of nominal resistance) as a Function of Frequency

General Radio Co. (U.S.A.). Type 516 *Units*

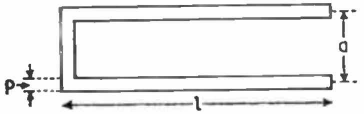
Decade Steps (Ohms)	Frequency in kc/s						
	50	100	200	500	1,000	2,000	5,000
	%	%	%	%	%	%	%
0·1	0·2	0·7	2	—	—	—	—
1	0·1	0·2	1	5	—	—	—
10	0	0	0·1	0·2	2	—	—
100	0	0	0	0·1	0·3	1	5
1,000	0	−0·1	−0·5	−2	−6	—	—
10,000	−2	−10	—	—	—	—	—

APPENDIX 1

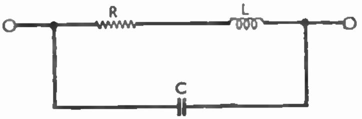
Analysis of Bi-Filar Winding

The resistance card may be simply represented by the network A hereunder, the symbols having the conventional meaning.

However, this "lumped" diagram is not truly representative as both L and C are distributed throughout the winding. In a typical case the resistance may consist of a wire doubled back on itself as shown in B, whence the impedance is that of a short-circuited transmission line. Provided the wires remain the same distance apart, the circuit representation is that of a "ladder" network comprising the electrical elements R, L, C and the shunt conductance G (used in the same sense as by Heaviside, *Electromagnetic Theory*, Vol. 1). Diagram C illustrates the network.

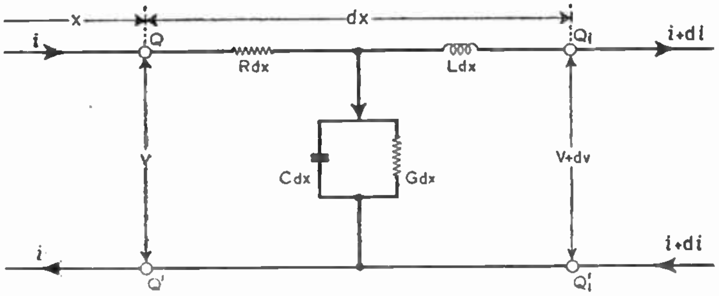


(B)



(A)

Let Q be at a distance x from an arbitrary origin and Q at a distance dx − x. The series impedance between Q and Q is $(R + j\omega L)$ dx and the shunt admittance $(G + j\omega C)$ dx. Let V be the voltage between Q − Q¹ and i the current entering at Q, we then derive :



(C)

$$- dv = i\,(R + j\omega L)\,dx$$
$$- di = v\,(G + j\omega C)\,dx$$

the first term being the volt drop between $Q - Q_1$ and the second term the admittance current from $Q\,Q_1$ to $Q^1\,Q^1_1$.

Hence :

$$\left.\begin{aligned} dv/dx &= -i\,(R + j\omega L) \\ di/dx &= -v\,(G + j\omega C) \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Eliminating v

$$d^2i/dx^2 = P^2 i.$$

Eliminating i

$$d^2v/dx^2 = P^2 v, \text{ where}$$

$$P^2 = (R + j\omega L)\,(G + j\omega C) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

and where P is the propagation constant.

Solving for v

$$v = A\epsilon^{Px} + B\epsilon^{-Px} \quad \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

The first expression in (1) then gives

$$i = -\left(A\epsilon^{Px} - B\epsilon^{-Px}\right) \frac{P}{R + j\omega L} = \frac{-(A\epsilon^{Px} - B\epsilon^{Px})}{Z} \quad \ldots\ldots\ldots\ldots (4)$$

where $Z = \sqrt{\left(\dfrac{R + j\omega L}{G + j\omega C}\right)}$

and is the characteristic impedance of the system.

If the line is shorted at $x = l$ then $v = O$
giving $O = A\epsilon^{Pl} + B\epsilon^{-Pl}$
so that $v = A\ \left(\epsilon^{Px} - \epsilon^{P(2l - x)}\right)$
and $\quad i = -\left((A/Z)\ (\epsilon^{Px} + \epsilon^{P(2l - x)})\right)$

At $x = O \quad v = A\ (1 - \epsilon^{2Pl})$

and $\quad i = -(A/Z)\ (1 + \epsilon^{2Pl})$

thus the impedance looking in at $x = 0$ is

$$\left(\frac{V}{i}\right)_0 = Z_s = -Z\,\frac{1 - \epsilon^{2Pl}}{1 + \epsilon^{2Pl}}$$

$$= Z\,\frac{\epsilon^{Pl} - \epsilon^{-Pl}}{\epsilon^{Pl} + \epsilon^{-Pl}}$$

$$= Z \tanh Pl$$

Note (1). $\quad \epsilon = 1 + \frac{1}{1!} + \frac{1}{2!} + \frac{1}{3!} + \ldots\ldots\ldots\ldots\ldots\ldots\ldots - 2{\cdot}71828$

Note (2). The constants A and B are given by the conditions at the beginning and end of the system.

APPENDIX II

Use of Hyperbolic Functions in Solution of Network C

The use of real hyperbolic functions (see *Plane Trigonometry*, Loney, Cambridge Univ. Press) leads to the first expression.

$Z_s \doteqdot Z\,(Pl - \frac{1}{3}P^3l^3)$ provided the line is electrically short and $|Pl| \ll 1$

$$\text{But } ZPl = \sqrt{\frac{R + j\omega L}{G + j\omega C}} \quad \sqrt{\left[(R + j\omega L)\ (G + j\omega C)\right]}\,l$$

$$= (R + j\omega L)\ l$$

and

$$ZP^3l^3 = (R + j\omega L)\ l\ (R + j\omega L)\ \ (G + j\omega C)\ l^2$$

so that

$$Z_s = (R + j\omega L)\ l\left(1 - \frac{1}{3}(R + j\omega L)\,(G + j\omega C)l^2\right)$$

$$= \frac{(R + j\omega L)l}{\left[1 + \frac{1}{3}\left(R + j\omega L\right)\ \left(G + j\omega C\right)l^2\right]}$$

$$\frac{\left[(R + j\omega L)l\right] \times \left[1/\frac{1}{3}\left(G + j\omega C\right)l\right]}{\left[(R + j\omega L)l\right] + \left[1/\frac{1}{3}\left(G + j\omega C\right)l\right]}$$

which is the admittance presented by $(R + j\omega L)l$ shunted by the admittance $\frac{1}{3}(G + j\omega C)l$. Thus the impedance of the wire doubled back on itself is equal to the resistance in series with the inductance shunted by one-third of the total capacity between the wires.

The inductance can be computed from

$$L = 0{\cdot}004l\,(\log h\ 2\ D/d - D/ + \mu\delta)\ \mu\ H$$

and the capacitance from

$$C - \frac{1{\cdot}11l}{2\cosh^{-1}(D/d)}\ \mu\mu F$$

APPENDIX III

Calculation of Impedance of a Resistance Element at Specified Frequency

Let diagram A represent a given resistance element. The impedance (Z) at frequency $\omega/2\pi$ is

$$\frac{(R + j\omega L)(1/j\omega C)}{(R + j\omega L + 1/j\omega C)}$$

$$= \frac{R + j\omega L}{1 - \omega^2 LC + j\omega CR}$$

$$= \frac{(R + j\omega L)(1 - \omega^2 LC - j\omega CR)}{(1 - \omega^2 LC)^2 + (\omega CR)^2}$$

The effective resistance is nearly equal to R in a well designed component, and the effective inductance is

$$L_{eff} = \frac{L(1 - \omega^2 LC) - CR^2}{(1 - \omega^2 LC)^2 + (\omega CR)^2}$$

$$\doteq L - CR^2$$

The time constant is then

$$T = (L - CR^2)/R = L/R - CR$$

For some value of D it is possible to make $L - 2\,CR^2 = 0$ whence the resistance becomes pure.

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DISCUSSION

Mr. A. V. Simpson (Member):

"The paper is an important one from the point of view of the behaviour of coils and resistors at high frequencies. Since it would appear that the ultimate goal in resistance attenuator design is zero phase angle at all frequencies, I hope that Dr. Blakey will indicate, from his experience, possible methods of solution.

"It has been stated that the best resistance attenuators have a negligible frequency error up to about 2,000 kc/s. and with an error that does not exceed 20 per cent. at 25,000 kc/s. when the output does not exceed 1 microvolt. With larger outputs the error is supposed to be less. The advantage of the resistance type of attenuator is that it is direct reading in voltage, but this advantage is lost if the error per increment of frequency change is unknown, and this appears to be the present state of affairs.

"If a resistance attenuator is terminated in its characteristic resistance there should be, in a theoretical sense, no reflection back into the network; under actual working conditions with an attenuator one cannot always terminate in the characteristic resistance. Is it right to assume that this non-correct termination would add to the normal phase-angle error of the attenuator? Information on this point would be appreciated together with possible increase in magnitude of error.

"One speaker mentioned the Piston type of attenuator as a possible solution to the shortcomings of the resistance network type. Having had some experience with the Piston type at centimetre wavelengths, I can state that it also has its shortcomings, and like the resistance type only gives an approximation to the truth. In most cases the attenuation of the Piston type is arrived at by calculation rather than by direct calibration, and here large errors are possible due to asymmetry of the leads to the coils and also other factors."

Mr. A. W. T. Atkin (Associate Member):

"Can Dr. Blakey state whether there is any frequency at which the manufacturer's calibration of the attenuator of a signal generator can be taken as reasonably accurate?

"Speaking of the inaccuracy of these attenuators at very high frequencies, I have often noticed that at, say, 15 M/cs, the output of an ordinary signal generator is so great, even with the attenuator set at zero, that a receiver undergoing a sensitivity test is hopelessly overloaded, with the output meter right off the scale."

Dr. Blakey:

"Replying to Mr. Simpson, I would state that the fundamental requirement is that the resistive elements shall be pure. This means that they shall be absolutely non-reactive and *ipso facto* have zero phase angle.

"I would, indeed, be a happy man were I able to give a panacea for all the ills of attenuation network. Truly I throw out a challenge with the express intention of stimulating vigorous thought about the present unsatisfactory position and in the hope that radio engineers will take active steps for its rectification.

"During the discourse I indicated a line of work I am following at the moment and which shows much promise. This is the use of just straight line filaments of Hoskins' alloy for each resistive element. The apparent advantage is that of the easily-derived computations for the reactive components from physical dimensions.

"Where Mr. Simpson says 'certain authorities' I think he means 'certain manufacturers.' The two terms are by no means synonymous. I would quote a phrase of Lord Kelvin: 'I know nothing of a thing unless I can measure it.' The answer to the wild claims made by such people is: 'Can they satisfactorily measure 1μV D.C., 1μV 50*l* or even 1μV 1000*l*?' The true answer is apparent. In the R.F. case can they measure even 1 volt with a degree of accuracy comparable with a simple first grade voltmeter at 50*l*? The answer is definitely no. Then follows the pertinent question: 'Do they allege the voltage division of their networks over six decades to be sufficiently accurate so as to give 1μV discrimination let alone 1μV absolute?' The errors accruing from variation of frequency are additive, generally speaking, to the initial errors mentioned above. I do not hesitate, therefore, in stating that the 'calibration' purporting to be μV, etc., are far removed from accurate.

" Incorrect terminations in networks introduce errors in the attenuation factor, and where other than purely resistive devices are used, a frequency factor is introduced.

" Although not originally intending to discuss the Piston type attenuator, I must agree with Mr. Simpson's views. He has by no means indicated all the sources of error in such devices, but I am sure he appreciates this also.

" In reply to Mr. Atkin, I would point out that the attenuator fitted to a Siemens & Halske signal generator appears to be reasonably good up to about 1 Mc/s. The Muirhead 'T' type attenuator of 600Ω characteristic impedance and 110 db. overall behaves quite well also up to 1 Mc/s, although it is fundamentally intended for audio frequencies. The German 'Körting' type (Dr. Dietz and Ritter) mentioned in the text has, in my view, a better standard of performance than any other type I have encountered.

" I concur with Mr. Atkin in his findings at high frequencies. Surely no greater proof of inaccuracies is needed."

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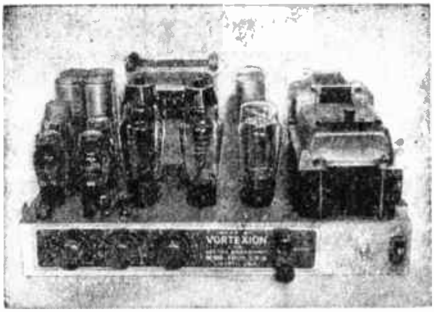

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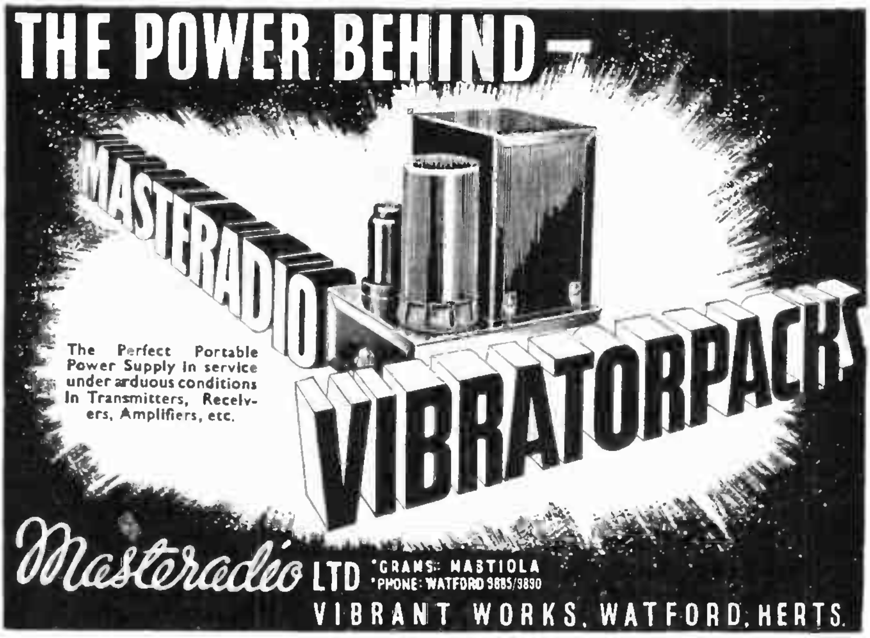

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The

British Institution of Radio Engineers

(Founded in 1925 as The Institute of Wireless Technology. Incorporated 1932.)

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AN ADDRESS TO ALL MEMBERS OF THE INSTITUTION

from

H. Leslie McMichael, M.I.E.E., M.Brit.I.R.E.

On his election to the office of a Vice-President of the Institution, Mr. Leslie McMichael attended his first meeting of Council on November 14th, 1941, and read the following address before members of the Institution on the 13th December, 1941.

"Gentlemen,

Forty years is a long time in any case and a very long time in radio history; yet it is nearly that time since, as a very raw apprentice, I found myself doing my first wireless experiments and since then I have found the subject more and more absorbing as the years have passed.

It is sixteen years since I first met some of the founders of this Institution. While some of us may have been rather disappointed with the rather slow development of the Institution, let us remember that our profession is the practice of the youngest branch of Engineering.

I was reminded of this fact when reading the Presidential Address of Dr. C. C. Garrard. You will recall that Dr. Garrard traced the foundation of Radio Science to 1873, and in view of this afternoon's paper,* I would like to remind you that May, an English Telegraph Engineer, discovered that light falling on to selenium caused a change in its electrical properties, other workers elaborated his ideas.

Evidence is certainly available that it is less than 90 years ago since the science of Radio and allied Engineering was first discovered. As a branch of learning and as a profession, Radio Engineering is less than 50 years old. Measured, therefore, with the progress of the established institutions representing the older branches of engineering, the progress of the Brit.I.R.E. has been commensurate with the growth of the Industry.

Irrespective of changing conditions and wars, the brotherhood of Engineers has existed ever since man commenced

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*"Barrier-Layer Photo Cell Applications" by J. A. Sargrove, M.Brit.I.R.E.

harnessing the forces of nature. The medieval Guilds were the forerunners of Engineering Societies and scientific bodies and the City Livery Companies of London were probably the first corporate bodies to give an impetus to the handicrafts which formed the basis of engineering as we know it to-day.

The Founders Company appears to have existed in an early form as far back as 1365, and the Armourers Company was granted a charter a century afterwards and as each branch of Engineering developed so did new Guilds or Institutions.

Although the British Institution of Radio Engineers is the youngest of the professional Engineering Societies, there is no reason why it should not rank with the older bodies in its policy and the standard of integrity required of its members.

The necessity for the existence of a professional body devoted solely to Radio and Allied Engineering cannot be disputed in this age of specialisation.

Specialised Training.

The question of specialisation in education is of paramount importance today, and I have been very pleased indeed to note the considerable time devoted by the officers of the Institution to this subject. Both in its scheme of examination and selection of papers read before Sections, the Brit.I.R.E. is able to provide for specialisation within the field of Radio and Allied science and engineering.

In the interests of the industry and of the profession, serious thought must continue to be given to the education of young people—our successors. The development of the industry will require a reservoir of young people properly taught the principles of the profession they are seeking to adopt.

In most professions there is a well beaten track of qualifications. Our chartered Institutions of Civil, Mechanical, Electrical and Automobile Engineers cater for engineers coming within those categories, and it is just as necessary to have proper qualifications for the Radio and Allied Engineer as it is for a Doctor to pass examinations in medicine and/or surgery.

Our Institution must be even more educational in its scope and far more serious in its purpose than it was in 1925, because the application of Radio and Allied science will grow to have a very great influence indeed upon the life of the world.

The Radio Engineer is the helping brother of the Aircraft Engineer for our airplanes depend on the assistance of radio in so many ways. The importance of our work not only justifies but demands the continued work of the Institution.

VICE-PRESIDENT

No more useful work is likely to be accomplished for many a year than the placing of Radio and Allied Engineering on a professional basis, and the recognition of this Institution as the representative body of that profession. By this means our Institution will have justified its establishment and its steady growth during the past sixteen years.

Membership.

Whilst membership and membership qualifications must necessarily remain strictly controlled, I would stress the importance of extending the power and efforts of the Institution by an increase in membership. It is essential to have connections through the Industry in order that we shall have collaboration and understanding in all matters connected with our profession, and it will obviously be of importance to the industry to have only those in our ranks who are eligible and suitable.

Here then, I suggest, are the present main structural parts of the Institution.

Firstly, to continue to recruit only those sufficiently qualified to enable the Institution to fulfill its purpose and aims.

Secondly, in our educational work we must assist in planning and affording facilities for examination in Radio and Allied Engineering, thus securing for the profession properly qualified material for employment in the profession.

Lastly, in our general programme, to offer the kind of subject we need for discussion and debate and the kind of speaker to introduce the subject.

In accepting membership, we accept a responsibility and the care of the three points above mentioned will help us to discharge that responsibility.

In all this work I am happy and indeed honoured to be associated. We have enthusiastic officers and a President who has given invaluable guidance. I, as a Member, appreciate the distinction of being elected a Vice-President at a time when I believe the Institution is assured of rapid development in keeping with the great progress made by the British Radio Industry."

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THE PROPERTIES OF NICKEL IRON ALLOYS AND THEIR APPLICATION TO ELECTRONIC DEVICES

by

G. A. V. Sowter, B.Sc.(Eng.), M.Brit.I.R.E., A.M.I.E.E.

(A paper read before the London Section of the Institution, at the Federation of British Industries, London, on August 30th, 1941).

The most important high permeability and magnetic materials are alloys of nickel and iron containing minor quantities of other elements. The fact that the magnetic performance of iron was surpassed by an alloy of iron and nickel has been known for many years (Panebianco, 1910, Yensen, *J.Amer.I.E.E.*, 1920, and others), but it was not until 1923 that serious commercial development took place. In that year, there was manufactured in this country the first Transatlantic Telegraph Cable with a nickel iron loading material (Permalloy) and this was followed soon afterwards by various Mumetal loaded cables (San Francisco—Honolulu, Cocos—Perth). The total length of laid submarine cable incorporating nickel iron alloys now exceeds 14,000 miles (all of which was manufactured in Great Britain) and undoubtedly

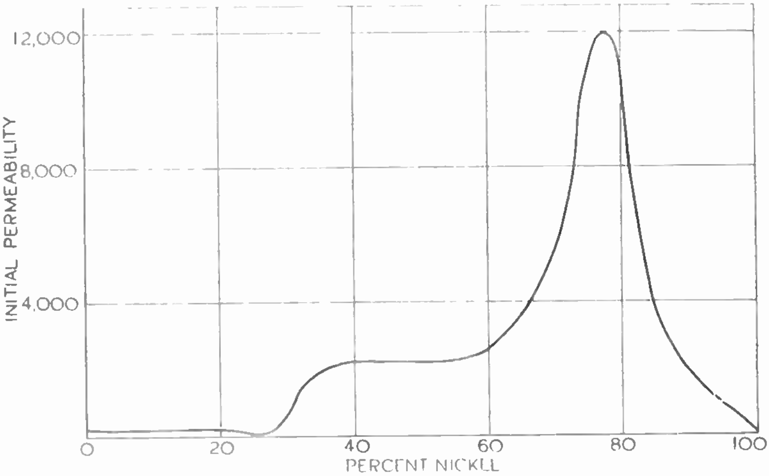


Fig. 1.—Curve showing variation of initial permeability of nickel iron alloy with variation of nickel content. The significient points occur when alloy contains 36%, 50% and 80% nickel.

this application gave an enormous impetus to the production of the nickel iron alloys for the multitudinous purposes for which they are now employed.

With regard to submarine cables, it is worth while explaining that the effect of wrapping round the copper conductor a small amount of nickel iron tape or wire greatly increases the inductance and thereby reduces the attenuation of the signal currents. This permits a higher operating frequency and enables a much increased volume of traffic to be handled. In the case of the 1923 Atlantic Cable, the increase of speed was fivefold as compared with the previous fastest cable.

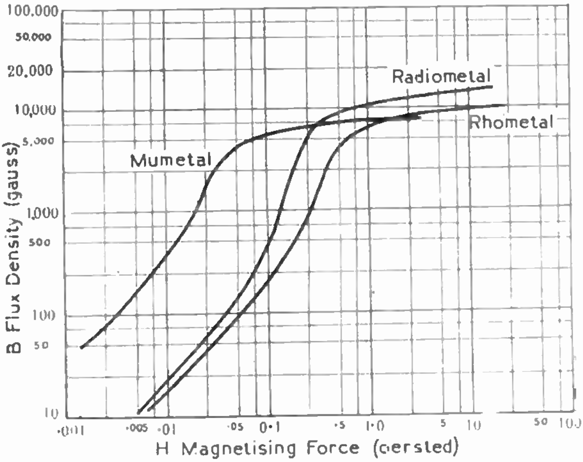


Fig. 2.—D.C. induction curves for Mumetal, Radiometal and Rhometal alloys.

Some time prior to this under the auspices of the Telegraph Construction and Maintenance Co., Ltd., a group of metallurgists and electrical technicians concentrated on the problem of high permeability materials and carried out intensive research on alloys with 80%, 50% and about 36% nickel content. The outcome of the work was the commercial introduction of the well known alloys Mumetal (78% Ni), Radiometal (48% Ni) and Rhometal (36% Ni).

My first introduction to Nickel Iron Alloys was in 1923, when I was engaged on measuring the magnetic properties of samples of nickel iron alloys produced in the Firm's Laboratories. Fig. 1 gives an indication of the variation of metal permeability with nickel content.

To obtain optimum magnetic properties and increase stability, the composition of these alloys has been adjusted by the addition of small proportions of Cr, Mo, Mn, Cu, but since this paper is to be devoted to the electrical rather than the metallurgical aspect, it is not proposed to discuss the individual effects of these elements. There exists also the Permalloy group of alloys, but in view of my close association with Mumetal, Radiometal and Rhometal, these will be considered exclusively. As a guide to the merits of these materials, the curves in Figs. 2, 3 and 4 are given, showing the relative properties obtained by direct current measurements.

Methods of Production.

The alloy constituents must be of the highest purity and are melted together in a high frequency furnace to avoid contamination. The resulting ingots are first approved on chemical analysis and then hot rolled to a pre-arranged thickness. A patented system of cold rolling is then employed[2] (British Patent No. 366,523—Smith, Garnett and Randall), which, apart from improving the material magnetically, has the effect of orienting the crystals so that they are aligned to give optimum properties along the direction of rolling. This is clearly indicated by a curve comparing the permeability of Mumetal rings with the equivalent spiral core construction. The maximum permeability of the strip core—flux running parallel to rolling direction—is 90,000, whereas the rings from the same strip have effectively a permeability of 55,000 only. It is interesting to note that this rolling technique, when applied to Silicon iron alloys, also improves their magnetic performance, and is leading to important developments.

Heat Treatment to Develop Properties.

Heat treatment of the alloys in their final form as strip or transformer laminations is absolutely essential if the magnetic properties are to be utilised. Thus, unannealed Mumetal

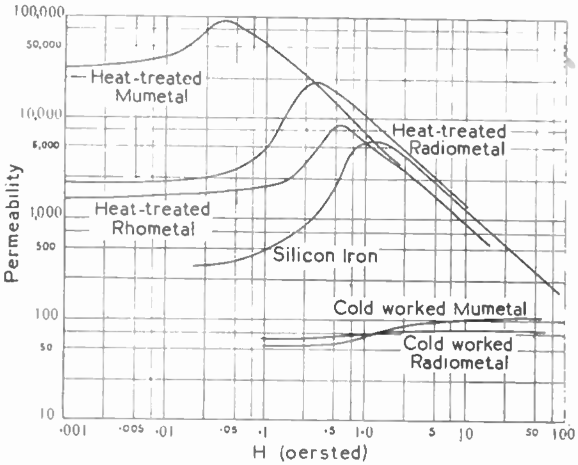


Fig. 3.—Comparative permeability curves for Mumetal and Radiometal before and after heat treatment. The value for cold worked Mumetal is increased many times by heat treatment.

has an initial permeability generally less than 100, but the effect of eliminating the strains imposed by the cold rolling is to increase the figure to 20,000—30,000 (See Fig. 3). In a similar manner, the other alloys, Radiometal and Rhometal, are vastly improved by heat treatment. This annealing process is quite simple, and consists of raising the material to a high temperature (1150°C. for Mumetal, 900-950°C. for Radio-metal), soaking and cooling slowly. The materials to be annealed should be treated in hydrogen or an inert gas, or else packed in sealed boxes. The technique is not difficult, but it requires some experience.

In connection with the heat treatment, it is interesting to note that the properties of Mumetal can be influenced by the application of a unidirectional magnetic field during the cooling. This results in abnormally high maximum permeabilities, 200,000 having been obtained by the Speaker on commerical material. The process, however, is difficult to control with the various shapes and sizes handled under normal conditions, and is not generally employed. It is worthy of note that Bell Laboratories reported some years ago that they had obtained a maximum permeability of 610,000 on a sample of 65% nickel iron treated in this manner under laboratory conditions. A similar treatment is now applied to the permanent magnetic materials Ticonel and Alcomax, which are subjected to unidirectional magnetic fields during cooling and have a vastly improved performance as a result. Actually, the B.H. product is doubled, and the remanence greatly increased.

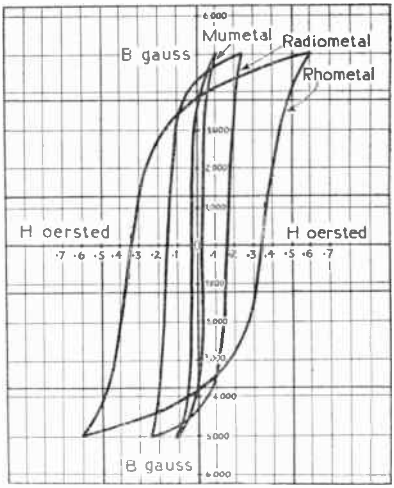


Fig. 4.—Comparative hysteresis loops for the three alloys, using D.C. measurements. The loss (ergs/cycle/cm³) is 38.5, 218 and 438 for Mumetal, Radiometal and Rhometal respectively.

Magnetic Properties of Mumetal, Radiometal and Rhometal.

Although a large amount of technical data exists on the properties of these alloys, it is not considered possible to publish all available curves in the Journal. The manufacturers of the alloys issue many of these in pamphlet form, and, for obvious reasons, only a brief summary of the properties is in the following table (Fig. 5) :

Summary of Properties of Mumetal, Radiometal and Rhometal as compared with Silicon Iron.

	Mumetal	Radiometal	Rhometal	Silicon Iron
Permeability, initial	10,000-30,000	2000	800-1500	300
,, maximum	100,000	22,000	8500	6000
Magnetising force for max. permeability (D.C.) (oersted) for	·037	·3	·55	1·2
Maximum flux denisty in gauss.	8000	16,000	10,000	18,000
Magnetising Force (D.C.) (oersted) for B = 5,000 gauss. B = 10,000 gauss.	·075 —	·24 ·8	·64 2	·9 2.4
Coercive force (oersted) for B max. = 5,000 gauss.	·03	0·1 – 0·2	·35	—
Hysteresis loss (ergs per cycle per c.c.) For B max. = 5,000 gauss	40 – 50	250	450	1800
Electrical Resistivity (Microhms per cm³)	60	55	95	61
Total Loss (Watts/lb) at 50 c/s. B max. = 100 gauss ,, = 1,000 ,, ,, = 10,000 ,, Sheet thickness .015″	·000016 ·0022 —	·00007 ·005 ·32	·00005 ·009 —	— — ·63
Specific Gravity (gm/cm³)	8·8	8·3	8·1	7·5

Fig. 5.

For Mumetal to be used at low frequencies there is an optimum thickness (0·01″), concerned with crystal structure, which results in highest permeability and lowest loss. The total A.C. loss (hysteresis, eddy current and "nachwirkung" or "disaccommodation effect") is the lowest of any commercial material, being only 1/30 that of silicon iron at B = 20 gauss and about ⅛ at B = 5,000 gauss.

The total loss loops can very easily be obtained by means of the Ferrometer Equipment (exhibited), or by the usual methods involving the cathode ray oscillograph apparatus.

The losses of the nickel iron alloys naturally increase with frequency and vary with thickness, since the latter has particular effect on the eddy current component. Curves giving this information exist, but the following table (Fig. 6) will be extremely helpful to designers requiring data at low frequencies. The losses are given by the following formula: $W = aB^x$, where W = total loss, a = a constant whose value is given in the table, B = maximum flux density (gauss) and $X = 2$ (approx.) The losses vary with f as indicated in Fig. 6 over the ordinary frequency range, and vary as the square of the thickness t for material about 0·15″ thick. For thin strip less than ·008″ thick, the loss varies as $t^{1 \cdot 7}$. The exponent of B is not always strictly 2, but generally approximates to this figure.

VALUES OF THE CONSTANT "a" in the loss Formula $W = aB^x$(watt lb.)

	Thickness	Frequency		
		50 cps.	1000 cps.	2500 cps.
Mumetal	.015	1.8×10^{-9}	1.9×10^{-7}	7.8×10^{-7}
	.005	1.99×10^{-10}	1.34×10^{-8}	7.73×10^{-8}
Radiometal	.015	8.8×10^{-9}	2.4×10^{-7}	1.25×10^{-6}
	.005	8.9×10^{-11}	4.6×10^{-9}	1.56×10^{-8}
Rhometal	.015	2.24×10^{-9}	7.6×10^{-8}	3.68×10^{-7}
	.004	5.8×10^{-9}	4×10^{-8}	1.28×10^{-7}

Fig. 6.

When a nickel iron core carries unidirectional flux as well as A.C. flux (e.g., core of series-fed intervalve transformer)

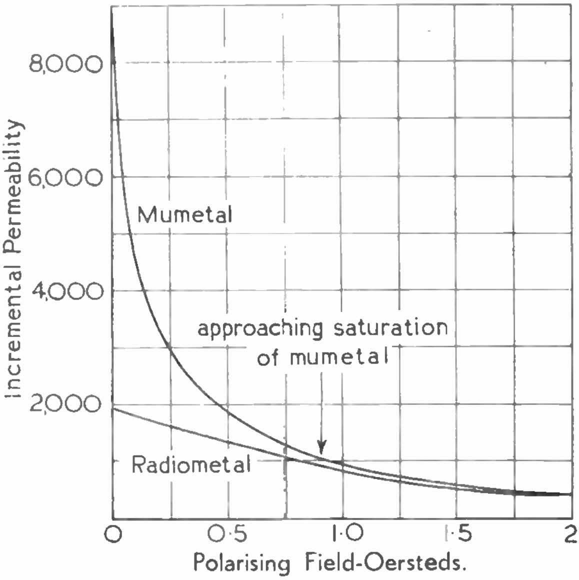


Fig. 7.—Incremental permeability curves for Mumetal and Radiometal, showing the effect of D.C. magnetising force on the cores. The curves were taken at 50 c/s with magnetisation of 0·005 oersteds Sheet thickness was 0·015″.

the effective permeability is reduced as for silicon iron, and the curve in Fig. 7 shows the extent of this reduction. It should be stressed that the earth's magnetic field has negligible effect on Mumetal for the normal shapes, as is explained elsewhere[2].

I am frequently asked if temperature is harmful to the magnetic properties. Soldering and bakelising involving temperatures up to 350°C. have no deleterious influence on Mumetal apart from slight effects due to mechanical strain, and it is found that with increase of operating temperature permeability is slightly improved and losses reduced. This opportunity is being taken of mentioning also that no permanent effect on properties can be brought about by the severest deliberate magnetisation. In all cases, the normal properties are easily restored by any of the conventional demagnetisation processes. Furthermore, the objectionable property of slow time change found with silicon iron is non-existent with nickel iron alloys.

Type of Mumetal Screen.	Thickness of Metal.	Screening Ratio measured by D.C. reversals and ballistic galvanometer.
(a) of Fig. 9 ...	.064 inch	600
(b) ,, ...	.064 ,,	400
(c) ,, ...	.032 ,,	150
(c) ,, ...	.064 ,,	230
(d) ,, ...	.032 ,,	80
(e) ,, ...	.032 ,,	40
(f) ,, ...	.032 ,,	30
	10 turns of .015 inch	400

Fig. 8.—Screening ratios of the cathode ray tube screens shown in Fig. 9.

Magnetic Properties: Methods of Test.

The methods of test used to determine the magnetic properties of the nickel iron alloys are briefly:—

1. Ballistic Galvanometer Method and Fluxmeter Method — for B - H - μ curves, pure hysteresis loss, coercivity and remanence.
2. A.C. Bridges of various types for B-H-μ-L-Q and total loss at various frequencies.
3. Wattmeter Equipment in conjunction with Lloyd Fisher Square for loss determination, form factor, B-H at 50 cps.
4. A.C. Potentiometer for purposes as 3.
5. Ferrometer apparatus for B-H-μ-W-Total loss loops—A.C. coercivity and remanence. (This apparatus was available for demonstration purposes and various recorded loops were shown).

Application to Electronic Devices.

There are a large number of uses of nickel iron alloys which cannot be discussed here, but the following summarised list indicates the scope of their application to electronic devices of interest to this audience:

Magnetic Screens	For oscillographs, C.R. tubes, transformers, chokes, mains units, motors, valves, etc.
Chokes	Smoothing, high inductance, filter units ((High Q).
Transformers	Line, input, microphone, intervalve, output, push-pull, photocell (transformer for cathode-follower devices preferred), high frequency (high coupling), pickup, tuned, wide band, mixing.
Television	Magnetic circuit deflector cores (tape or laminations), rotors and stators for mechanical system, scanning transformers, frame transformers.
Recording and Reproducing Gear	Blattnerphone needles, pickup armatures, pole pieces, cutting head components.

Mumetal Screens.

A variety of screens are exhibited, and reference is made to articles which have been published giving general rules of design refs. 3, 4. In particular, with regard to screening boxes for transformers, the thickness of Mumetal is of importance, but the fit of the lid, the number of holes and the extent of the overlap have great influence on the performance. As a case in point, a Mumetal box 3″ cube showed a 30 dB reduction in pickup at 50 cps. whilst a box 1″ cube made from the same

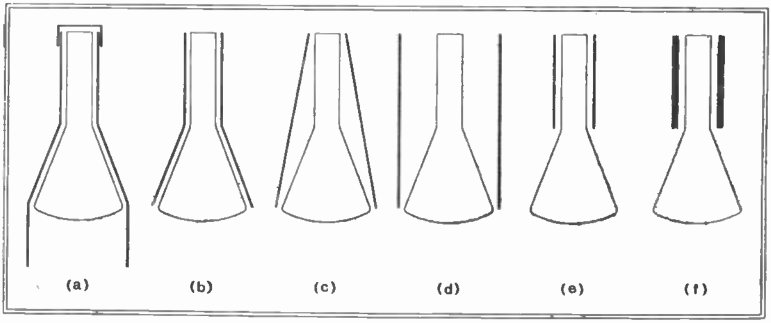


Fig. 9.—Cross-section diagrams of Mumetal cathode ray tube screen shapes. Associated data appears in the table (Fig. 9) opposite.

piece of sheet annealed with the former showed a reduction of 40 dB. From this it can be inferred that the smaller box offered less chance of flux entering by the lid joint to the extent of 10 dB difference in performance. With regard to cathode ray tube screens, screening ratios measured by reversal of flux and using as detector a search coil associated with a ballistic galvanometer, have given screening ratio figures as indicated in Fig. 8.

The general shape of the screens measured is indicated in Figure 9.

The Table (Fig. 10), due to Constable and Aston at N.P.L.,[5] indicates clearly the relative merits of Mumetal and other screening materials, and may be of value to members of this Institution.

Transformers.

Particular interest is centred around the design of transformers, and the use of nickel iron alloys has improved performance out of all recognition. In general, transformers are restricted to voltage devices operating over various frequency bands, but small power and output transformers are made where electrical requirements are severe and cost is secondary. As an introduction to design, consider the most elementary case of winding a 100 H choke to operate on low voltage A.C., the winding resistance being unimportant. The cheapest core would consist of 12 Mumetal laminations type No. 31T., 0.015 inches thick, assembled in the most compact form. It is simple to measure the average path of the flux, (l_m) as 7.2 cm. and to deduce the mean sectional area (A) as 0.28 cm².

Frequency cycles per sec.)	Transformer Iron thickness 1/64"	Steel thickness 1/16"	Copper thickness 1/32"	Lead thickness ½"	Brass thickness ¼"	Aluminium thickness ¼"	Cast Iron thickness ¼"	High Permeability Alloy thickness 1/16"	
								Enclosing pick-up transformer	Enclosing exciting transformer
	db.	db.	db.	db.	db.	db.	db.	db.	db.
50	4	6	4	4	10	12	12	36	30
100	5	6	5	7	12	17	13	37	28
200	4	6	8	10	16	20	16	36	29
400	4	7	12	16	22	26	24	35	29
800	4	7	18	24	30	32	41	34	30
1600	6	8	24	32	40	31	33	32	29
3200	6	6	26	22	30	20	20	26	22
6400	8	6	13	8	15	8	8	20	8

Fig. 10.—Table showing comparative screening efficiency of Mumetal and other metals at various frequencies.

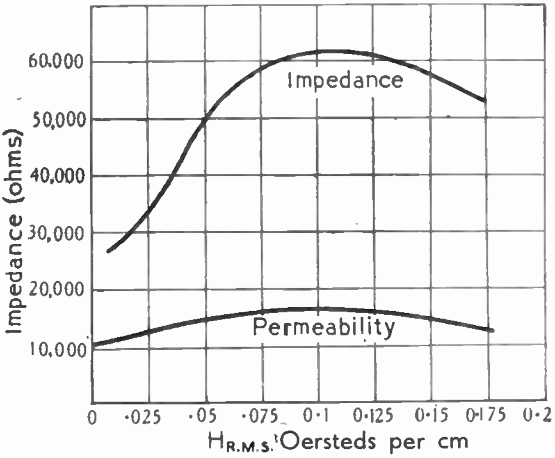
Assuming the initial permeability of the Mumetal to be 10,000, the turns (N) are easily computed from the well known formula:—

$$L = \frac{4\pi N^2 A\mu}{10^9\ l_m}$$

L = inductance in henries
μ = permeability under operating condtions.

From this it is seen that 4,470 turns are required. The gauge of wire to be used is determined in the conventional

Fig. 11.—
Curves demonstrating the change in impedance with change in magnetising force explained in the text below.



manner, and no further comment is necessary except to stress the fact that Mumetal laminations should not be bent during assembly or hammered so that they are strained beyond the elastic limit. Where laminations are bent—and this has been known—the permeability will be reduced in the region of the bending but can easily be regained by correct heat treatment.

This 100 H choke, used at 50 c/s, will be quite stable in its properties, but naturally will increase in inductance and impedance with increase of magnetising force or applied voltage. This is illustrated in curve Figure 11. The extent of this increase (about 60% for inductance or permeability and 150% for Z) is not large as compared with a closed core silicon iron choke, where variations of the order of several hundred per cent. occur.

Like most magnetic materials, the effective permeability of nickel iron alloys decreases as the frequency is raised, so that the 100 H choke designed for 50 cps. operation will have an inductance of approximately 30 H at 1000 cps. Nevertheless, the impedance Z, $(R + j\omega L)$, increases with frequency, so that where a choke is regarded as a load in an amplifier, for example, a design for 50 cps. is the best method of tackling the problem. It should be borne in mind, of course, that a choke is, in effect, a tuned circuit, and the foregoing argument refers to frequencies well below the natural resonance.

It is here convenient to mention that, when a choke carries D.C. as well as A.C., the design is slightly modified. Under these conditions, the "incremental permeability" is used in the formula and is read from curves Fig. 7. Given the value under exact operation conditions for a closed magnetic circuit, the inductance of a choke carrying D.C. is easily estimated. It is invariably lower than the figure obtained when the choke is handling the original value of A.C. alone.

For the best utilisation of magnetic material, chokes handling D.C. and A.C. simultaneously are normally gapped. The reason for this is that the gap reduces the effect of the D.C. polarisation of the core material and thus increases the incremental permeability in spite of the influence of the gap on the A.C. reluctance. A curve (Fig. 12) is given (similar to that evolved by Hanna[6]) which enables the optimum turns and the gap to be deduced for any stack of Radiometal required for a particular inductance value with known strengths of D.C. The curve is practically self-explanatory, and no further comment appears to be necessary.

A typical design for a 50 H choke carrying 20 mA D.C. is as follows:—

Laminations: Radiometal, 101T type, 0.015″ thick, square centre section. Referring to curve (Fig. 12):

$$\frac{LI^2}{V} = 460; \quad \frac{NI}{l} = 9{,}700; \text{ and } \quad \frac{a}{l} = .0016.$$

From this is follows that the turns are 6,500 (wire to be suitable for 20 mA D.C. + A.C.) and that the air gap is 0.021″ (say 0.01″ in each limb). Messrs. McFadyen and Spinks have carried out a certain amount of research on choke design and suggest that the Hanna curve gives slightly pessimistic results. This is no great disadvantage in practice, particularly as the discrepancy is well within the limits of variation of the magnetic material. Whilst on the subject of chokes, the question of "High Q chokes" arises, and here the nickel iron alloys are of enormous value to industry. As is well known, a choke is said to have a high magnification or Q value when $\frac{\omega L}{R}$ is large, ω being $2\pi \times$ frequency (c/s), L the series inductance and R the effective series resistance. For power and low audio frequencies there is nothing to surpass nickel iron as the core material, where it is even superior to dust cores, so noted for their H.F. performance.

The question of design is now rather more complicated, and involves a certain amount of experience for the best choice of material. Invariably the laminations are assembled with a designed air gap, and thin materials are important for operation at frequencies somewhat in excess of 50 cps. Thin stampings are not much influenced by a change of frequency (thus 0.005″ thick Mumetal may have an initial permeability of 10,000 at 50 c/s. and 9,000 at 1,000 c/s.) and, owing to the reduction in eddy currents, the total loss is much less than that of the usual 0.015″ thick material. A high "Q" choke is obviously one in which the permeability is the highest possible and the loss is reduced to a minimum. The loss consists of copper loss, I^2R_c, due to the winding (and including dielectric and insulation losses) and core loss I^2R_f due to the magnetic

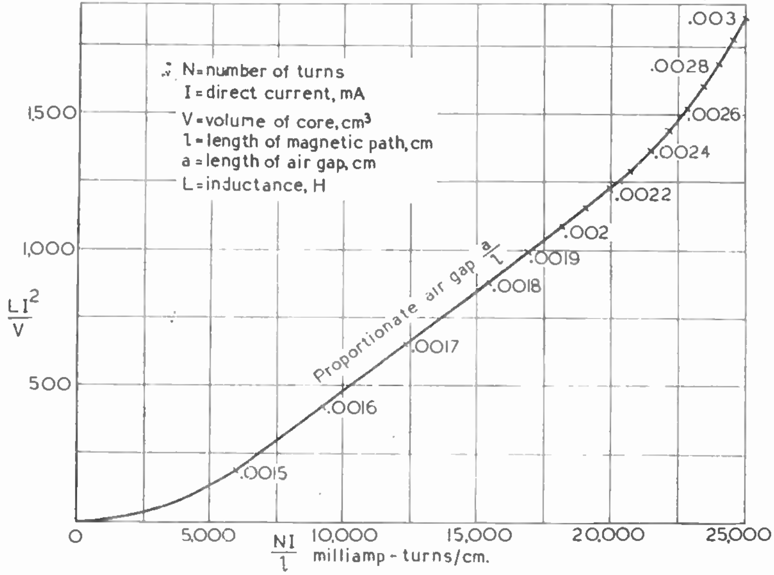


Fig. 12.—Inductance curve for gapped Radiometal core, taken at 50 c/s, 0·05 oersteds. From this curve can be derived the optimum number of turns and length of gap, if the D.C. and inductance values are known.

material. To understand clearly the factors involved, assume there is available a square centre section of one of the normal laminations in Mumetal 0.015″ thick. On a bobbin it would be possible with various gauges of wire to make a whole series of different windings having different resistances. Furthermore, by assembling the laminations in such a manner that a gap in the magnetic circuit can be produced and varied at will, it is also possible to vary considerably the inductance due to any particular winding. Now it can be shown theoretically that the highest value of Q is obtained in any assembly when the iron loss resistance is equal to the coil loss resistance, the latter being known for any winding. The iron loss resistance for the core under consideration depends solely upon the operating flux density and the frequency, so that if these are fixed, the value of R_f can be deduced from guarantee curves or measurements. The question of design then resolves itself into manipulating the type of coil and air gap until $R_c = R_f$, and fortunately, this is neither difficult nor critical. As a guide to the performance to be expected, the following figures for high Q chokes with nickel iron cores using different stamping sizes are quoted from measurements made on finished products.

L (henries)	Q ($\frac{\omega L}{R}$)
(a) 3	30 at 100 cps.
(b) 1	50 at 800 cps.
(c) 1	> 100 at 1000 cps.

It is known that insulating the laminations is of high importance to keep down the eddy current loss component. On any choke it is found that the inductance value varies little with frequency over certain ranges, owing to the influence of the air gap reluctance, but the optimum Q value occurs at a definite frequency.

Audio Frequency Transformers:

It has been shown already that a small stack of 31T type lamination in Mumetal, 12 in number, wound with 4,470 turns, has an inductance of 100 H at 50 c/s. Obviously, if a winding of 12,000 turns were made, a tapping could be made at 4,000 turns to give an inductance of approximately 80 H for this section. The choke could be used as a midget auto transformer where 4,000 turns is the primary winding and 12,000 turns (the whole winding) is the secondary. This, in fact, represents the design of a very common type of parallel-fed intervalve transformer, of which tens of thousands have been made. The coupling condenser is normally about 0.2 μF which, resonating with the primary inductance, accentuates the bass register in the region of 35 cps. The overall frequency response is remarkably good up to 10,000 c/s, and in my opinion, the only drawback of the whole design is the use of the very fine wire involved. This limits the voltage which can be handled, and the wire is prone to suffer from the effects of corrosion. Somewhat larger laminations are to be preferred for high quality performance, and almost invariably, separate primary and secondary windings are employed. The question of design, insofar as primary inductance is concerned, is simple, but experience alone dictates the best winding arrangement.

General Design of Transformer.

For intervalve, input, microphone, line and push-pull voltage transformers to cover the audio-frequency band the method of design is common. Assuming the signal source to be represented by a generator having a series resistance R, the primary inductance L_p should be such that, at the lowest frequency to be considered and for the weakest signal, the value ωL_p should be reasonably larger than R. The exact amount larger is determined by the permissible dB drop at this lowest frequency, and merely involves the solution of the elementary triangle formed by the factors R, $j\omega L_p$ and Z, the latter being the vector sum of R and $j\omega L_p$.

The upper frequency response will be dependent upon the leakage inductance L_e, which is concerned with the relative disposition of the primary and secondary windings. The most elementary equivalent circuit diagram of these types of transformer is that given in Fig. 13, which is generally known.

A series resonance can occur between L_e and C, and the magnitude of the voltage set up across C is controlled by the current which R permits to flow. Obviously, with a low resistance generator, (e.g., valve of low impedance) this current will be large, and the upper register can actually be accentuated in the leakage resonance frequency region f_e. Beyond the frequency f_e, the voltage output of the transformer falls off fairly rapidly. Now the advantage of the use of high permeability alloys is not so much due to the effect of their presence on leakage inductance, but because, for any particular winding, the primary inductance L_p is so much increased by the use of a high permeability core. It can be shown that the number of octaves which a transformer can handle adequately depends upon the ratio of L_p to L_e. A good design, then, is one in which the best high permeability alloy and stamping is chosen for the core, the winding being so proportioned and sectionised that L_e is reduced to a minimum and adequate room is available on the bobbin for suitable insulation. On the question of voltage handling capacity, this is limited by the permissible distortion, which is considered later.

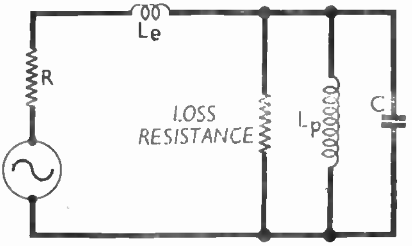


Fig. 13 — *Equivalent transformer*

Typical Series-fed Intervalve Transformer Design.

When the voltage transformer is one carrying the D.C. as well as the A.C., it may not be necessary to introduce an air gap except in special circumstances. The design is approached in exactly the same manner as for the parallel-fed example considered, but the permeability is now read from the curve,

Fig. 7. For a given number of primary turns N the polarising force H_p is estimated by the formula $H_p = \frac{0.4\pi I N}{l}$ and the following information is given as an example:

Core: Radiometal, No. 24T type lamniatios 0.015″ thick.
Primary turns = 4,000.
Secondary turns = 12,000.
l_m = 17.2 cm.
A = 5.5 cm².
Lamination stacking factor 95%.
D.C. passing through winding 3 m.A.

H_p is calculated to be 0.88, whence L_p is estimated as 63 H for the weakest signal. When no D.C. flows, the inductance is 130 H.

It should be mentioned that Mumetal is sometimes used for transformers operating under incremental conditions where the H_p is not sufficiently large to cause saturation to be approached.

For design purposes, it is possible to construct a family of curves for a particular lamination assembly in each nickel iron alloy indicating the effective permeability for different values of H_p with various air gaps. This enables the choice of material to be made easily and gives the optimum performance of the material. For gaps less than 0.001″ it is usual to interleave stampings in sets of 12, 9, 6, 4 or less. This will introduce a certain amount of reluctance into the magnetic circuit and give a fairly fine control of gap under certain conditions.

Output Transformers.

Nickel iron alloys are employed for output transformers where expense is relatively unimportant but the the highest quality reproduction is desirable both with respect to frequency range and wave form distortion. The previous considerations relating to general design still apply, but now the operating flux density must be taken into account at the lowest important frequency, and the winding resistances are no longer negligible. Time will not permit a detailed treatment, but to indicate practical possibilities, the tables on page 115 (opposite) give the performance figures of transformers actually constructed by the Speaker.

The performance of all these transformers is particularly good; but it is repeatable with commercial material. It is not claimed that these represent the optimum design for the conditions stated, but the performance adequately fulfils the requirements.

Unfortunately, in this paper one cannot discuss all the applications listed, but it is worth while briefly mentioning H.F. transformers incorporating nickel iron alloys.

Wide Band Transformers.

Work is now in progress in well known laboratories on wide band transformers operating over various sections of the frequency range 50 Kc/s to 3 Mc/s, and some very successful designs have been evolved with thin strip nickel iron cores. These retain their permeability up to high frequencies, and thus necessitate very few turns for the windings. This leads to small residual capacities, and enables a balance of the circular parameters (L, C, R, etc.) to be made, since this transformer may be treated as a special type of filter. Little imagination is required to realise the importance of such transformers and, without desiring to steal the thunder of the technicians engaged, it can at least be stated that these transformers will lead to important developments in communication and television distribution.

Performance, Level Figures of A.F. Transformers.

Frequency Cps.	Output Transformer (carrying anode current). (decibels)	High Fidelity microphone Transformer. Ratio 60/1 for use with 8 Ohm mic. (decibels)	Push-pull Intervalve Transformer. Overall ratio 1/2.5. (decibels)	Midget microphone Transformer. Ratio 60/1 for 8 ohm. mic. (decibels)	
20	—3.7	— 1	—1.4	— 3.4	
50	— 1	— .4		—1.4	
70	— .5		— .7		
100	— .3	— .2		— 0.9	
200	— .2	0	— .3	—0.5	
500	0	0	0	0.3	
1000	0	0	0	—0.2	
2000	0	0	0	0	
3000	0	0	0	0	
5000	0	0	0	0	
7000	0	0	0	0	
8000	0	0	0	0	
9000	0	0	0	0	
10000	0	0	0	.3	Rising Characteristic
12000	0	0	0	.5	
14000	0	— .1	0	.6	
16000	0	— .2	0	.9	
18000	0	— .3	0	1.2	
20000	— .1	— .7	— .1	1.5	
22000	— .3			1.7	
24000	— .8				
25000	— .9				
30000	—2.7				

Rhometal cores have been in use for some years for bridge coupling transformers operating at frequencies up to 1 Mc/s. and it is claimed that coupling coefficients of the order of 99% are possible at this frequency.

Television Transformers.

For television receivers, Rhometal laminations have been widely used in the form of scanning and line transformer cores. The design of scanning transformers has been considered elsewhere by the Speaker,[7] where it is shown that the signal pulse of saw-tooth waveform can be represented by the following Fourier Series:

$$Y = 2(\text{Sin } x - \tfrac{1}{2}\text{ Sin } 2x + \tfrac{1}{3}\text{ Sin } 3x - \tfrac{1}{4}\text{ Sin } 4x + - \ldots\ldots\ldots\ldots).$$

For the usual system of transmission, this saw-tooth pulse is produced approximately 10,000 times per second, and for faithful reproduction of the pulse, the transformer must handle the harmonics indicated in the above series. It is conventionally agreed that harmonics up to the twentieth are of importance and the transformer must, therefore handle components at 200 kc/s. Owing to high resistivity and the consequent limitation of eddy current effects, the permeability of Rhometal falls but slightly with increase of frequency, whereas other alloys, particularly silicon iron, show an appreciable drop. An actual design is given in the article mentioned, and the reader is referred to this for all details.

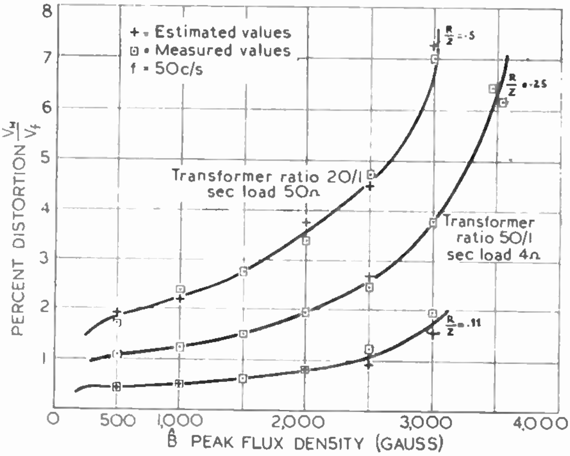


Fig. 14.—3rd harmonic distortion curves for Mumetal Transformers showing estimated and measured values. These are deliberately designed to be high to substantiate the theory of distortion prediction.

Distortion in Audio-Frequency Transformers.

In spite of its importance in realistic reproduction, the question of distortion in transformer cores has only received attention during the last two or three years. An excellent series of articles was given by Mr. N. G. R. Partridge in the *Wireless World*[8] some two years ago wherein he investigated thoroughly the distortion of silicon iron. He showed that to a first approximation the percentage distortion could be given by the formula:

$$\text{Percentage distortion} = X \frac{R}{Z_f}$$

X = a basic factor of the material given in curves.
R = equivalent parallel resistance of external load (referred to py.) and valve.
Z_f = Primary impedance at fundamental frequency.

At the suggestion of Mr. Partridge, and using a modified form of this expression I have carried out a fair amount of research on the distortion of Mumetal, Radiometal and Rhometal, the work is still proceeding, but the method employed has been established, and in due course it is proposed to publish full data for these alloys. A small amount of information has already been made known,[9] but no details of application to design problems have been stated. To verify the theory associated with my research, curves Figs. 14 and 15 have been produced in connection with transformers deliberately designed to give excessive distortion. The values shown are considerably in excess of what exists with conventional design but were necessary to enable the theory to be substantiated. The curves show the predicted distortion for transformers operating with various ratios and loads, and spot points are added to indicate the results of actual measurements. The agreement is remarkably good, and it is hoped in the near future to carry out further experimental work with a view to determining the possible variation of distortion with commercial material.

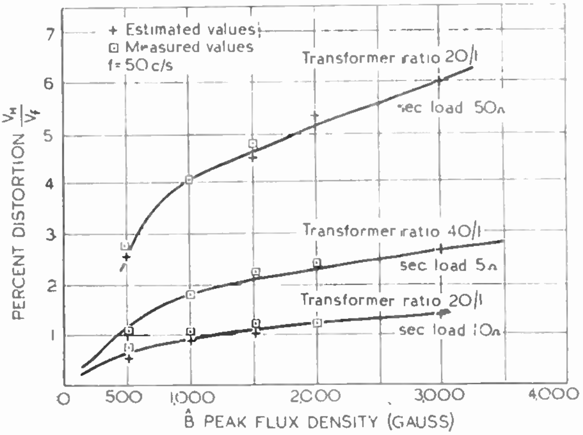


Fig. 15.—3rd harmonic distortion curves for Radiometal Transformers. Close agreement is seen to exist between estimated and measured values. These are deliberately designed to be high to substantiate the theory of distortion prediction.

DISCUSSION.

Mr. Sowter:

"To open the discussion, I will ask Mr. Garnett to address you since he was very much concerned with the early work in this country which led to the investigation and commercialisation of nickel iron alloys of the Mumetal family."

Mr. Garnett:

"Whilst appreciating very much Mr. Sowter's kind reference to my efforts I would say that it is men like Mr. Sowter and Mr. Randall who made this sort of work possible. As far as I recollect, my first impression of the value of nickel iron alloys was contained in a paper published many years ago. Here I think a statement was made that some of these alloys, especially one containing 36% nickel, deserved much more attention, the properties being so much better than the best sample of Swedish iron. I think that was the remark made and out of it we arrived at the present series of nickel iron alloys which are known to the radio public on their own merits. I hope that development will go very much further."

Mr. Humphreys:

"In thanking Mr. Sowter for his past co-operation on the design of Mumetal screens, I am interested to note the Paschen Galvanometer Screen exhibited where the material is "pop-marked" to obtain the optimum spacing between layers. We found in commercial practice that "pops" on Mumetal are tedious to make and the simple expedient of employing "Durex" tape was very much better and cheaper."

Mr. Sargrove:

"There is a question as to why magnetic screens are made for valves. Manufacturers have endeavoured to cheapen the valve material and instead of using nickel are trying to use iron nickel-plated, which is susceptible to stray magnetic fields. Another application for this type of Mumetal screen is with the barretter which mainly consists of an iron wire. The screening would stop all filaments from vibrating under magnetic influence and might increase the life of this device from 1,000 to nearly 10,000 hours. This might be well worth trying."

Mr. Bocking:

"Are any cores available for use at ultra-high frequencies?"

Mr. Sowter:

"A good deal of work is being carried out with thin strip and wire but little can be published concerning the results. Rhometal tape about .002" thick has a permeability of 100 or so at 1 Mcs. and is used up to frequencies greatly in excess of this."

Dr. Garrard:

"Can nickel iron be employed for mass production chokes? Also, can the Ferrometer be used for silicon iron testing?"

Mr. Sowter:

"The alloys are fully capable of giving the electrical performance for less material but it is a question of economics. For this application, the cost would preclude the use of Radiometal. Regarding silicon iron loss measurements, it is claimed by the Makers that the Ferrometer is quite suitable for silicon iron testing. I personally have carried out with it hundreds of measurements on Mumetal and other alloys and find very good agreement with the results obtained by other methods, such as the A.C. bridge or A.C. potentiometer. Discrepancies begin to occur only when an appreciable distortion of the wave-form sets in, and to my mind, the question of method of control, type of winding and nature of specimen are of prime importance. Figure 16 indicates the wave forms to be expected with Mumetal and silicon iron at saturation and shows clearly the nature of the difficulties."

"Without wishing to discuss now the exact theory of the Ferrometer, which involves perfect mechanical synchronous rectifiers and an 'ideal' transformer, there appears to be no reason why exact measurements should not be carried out on silicon iron. If, however, impure wave forms are submitted to the instrument, imperfect results will be obtained. The difficulties likely to be encountered are obvious when these families of B.H. loops are considered" (demonstration of various curves on B.H. loops and wave-forms).

Mr. Lane:

"Can the nickel iron alloys be employed as core materials for H.F. instrument transformers for indicating say feeder current?"

Mr. Sowter:

"It is known that straight-through transformers of this type using thin Rhometal strip have been manufactured and sold by Messrs. Elliott Bros. Ltd., but the device is by no means in general use."

Corresponded question:

"It is understood that the Ferrometer demonstrated by Mr. Sowter can produce A.C. hysteresis loops. Is there not a method known using a C.R.O. Tube?"

Mr. Sowter:

"Yes, it is possible to obtain loops with a cathode ray tube and I recall many years ago that one of the first tubes made by Cossor incorporating a filament was purchased by

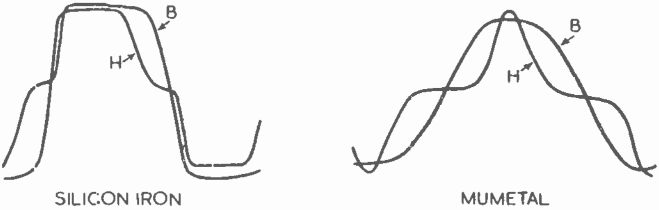


Fig. 16.—*Waveforms showing the distortion to be expected with saturated silicon iron and Mumetal cores.*

us for this purpose. The first thing we did was to break off one of the platinum electrode wires within a few hours of delivery of the tube, which cost £40. This was a blow, but a little metallic paste overcame the difficulty. A wooden structure was fitted round the tube containing four coils into two of which were placed on different occasions samples of Mumetal, Radiometal and pianoforte wire. We were able to get pictures by using an external camera with an appropriate attachment but we never used any measurements on the loops because of the doubt regarding the exact value of magnetising force H with the short rods employed. Another method with a ring sample was subsequently adopted and involved a condenser-resistance device to differentiate voltage to flux density B. This is now well known and is published in the leaflet on the Oscilloscope or its equivalent. The results obtained are not of a precision nature however unless one does get pure differentiation."

Mr. Sargrove:

"In thanking Mr. Sowter for his excellent paper, I remember a passage I recently read in a book on logic, in which it was stated that ". . . an investigator and research worker must not only be honest and intelligent, but above all, be well informed." Well, Mr. Sowter has been honest in his disclosures, by giving us the disadvantages as well as the advantages of his products, in his research work he has been most intelligent and, I think, one must agree that above all he is well informed, and in his lecture he has given us the benefit of all these virtues. He has given us a lot of good ideas and I think he will be pestered with a lot of telephone calls." (Laughter).

A vote of thanks was proposed by Dr. Garrard and was unanimously acclaimed.

Mr. Sowter:

"I thank you for giving me so much of your time and for the very fine reception you have accorded my paper. It has given me great pleasure to see so many old friends."

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(2) Smith, Garnett & Randall—Brit. Patent No. 366, 523.
(3) Sowter—*Wireless World*—Aug. 14th, 1936.
(4) Randall & Sowter—J.S.I., Vol. XV., No. 10, Oct., 1938.
(5) Constable and Aston—J.S.I., Vol. XIII, 1936 (295).
(6) Hanna—*J.Amer.I.E.E.*—Feb., 1927.
(7) Sowter—*Television and Short Wave World*—April, 1937.
(8) Partridge—*Wireless World*—June 22nd-29th.
July 6th-13th, 1939.
(9) Storey—*Wireless Engineer*—Vol. XV., Feb., 1938.

The British Institution of Radio Engineers

(Founded 1925 as The Institute of Wireless Technology. Incorporated 1932)

Active Membership.

All members are urged to identify themselves with the Institution by participating, whenever possible, in Brit. I.R.E. functions, particularly Section meetings, and on such occasions to make themselves known to other members.

It should be clearly understood that a member of any other centre and the Graduates and Students are, for the duration of hostilities, welcomed at all meetings.

Corrigendum.

Journal, vol. 2-3, p. 74. The second formula reads:—

$$L=\frac{\lambda}{2\ \text{Sin}\ 2}$$

which is incorrect.

It should read as follows:—

$$L=\frac{\lambda}{2\ \text{Sin}^2 8}$$

The Journal.

Will members please note that copies of the March/April, June/July, and Sept./Oct., 1941, Journals are no longer available, the small surplus stock now being completely exhausted.

A few copies of the bound proceedings, volume 1, are however, still available at 12/6 post free to members only.

Benevolent and Building Funds.

Owing to paper shortage lists of subscribers to the Benevolent and Building funds has had to be left out of this issue, but will be included, if possible, in the March, 1942, issue.

Graduateship Examination.

The results of the November, 1941, examination has been circulated to all candidates and publication of the list of successful candidates, together with the awards made for the 1941 examinations will be given in the March Journal.

The next examination will be held on May 15th and 16th, 1942. Will intending candidates please note that applications to sit must be lodged not later than March 31st, 1942, and that late entries will **not** be accepted.

Section Meetings.

London Section—at Federation of British Industries, 21 Tothill Street, S.W.1.
7th March, 1942—"Harmonic Distortion in Audio Frequency Transformers" by N. Partridge, B.Sc., M.Brit.I.R.E., A.M.I.E.E.

London Section—9th April, 1942. "Wired Broadcasting," P. P. Eckersley, M.I.E.E.

South Western Section—at Bristol University, Bristol, 3.30 p.m.
14th March, 1942—"Wave Guides" by G. Wooldridge, B.Sc., Assoc. Brit.I.R.E.

JOURNAL OF FHE

British Institution of Radio Engineers

APPLICATION OF THE CATHODE RAY OSCILLOGRAPH IN ENGINEERING.

by

W. Wilson, D.Sc., B.Eng., M.I.E.E., M.A.I.E.E.

(A paper read before the Midland Section of the Institution, held at The University of Birmingham, on October 15th, 1941.)

One of the chief developments in connection with the use of electrical instruments during the past decade has been the rapid adoption of the cathode ray oscillograph in many branches of the industry, even including heavy electrical and mechanical engineering. At first sight it seems surprising that so philosophical a piece of apparatus should find employment in connection with work of so diametrically opposite a nature to itself; but the actual facts are that not only has the cathode instrument proved itself the rival of the electro-magnetic oscillograph, but has surpassed the latter in a number of important respects; and further, it is displaying similar advantages over other and much simpler instruments, such as indicating voltmeters and ammeters, and even mechanical instruments like the steam engine indicator.

Advantages of Cathode Ray over Electromagnetic Oscillograph.

As a criterion of its capabilities, its various advantages over the electro-magnetic oscillograph may be quoted. These are as follows:—

(1) It is suitable for use with the highest known frequencies, and will give extremely high writing speeds, of the order of 50 to 200 miles per second.

(2) It is far more versatile than its older rival. Whereas the latter could only be used with a linear time base, usually provided by a rotating drum, the cathode oscillograph can record its indications by means of many types of time base, including such convenient ones as the elliptical, spiral, and zig-zag types; while any other quantity can be used as the base, or horizontal co-ordinate.

(3) The instrument is far more robust than that employing the delicate mirror-suspension, which is easily ruptured not only by rough usage or transport, but also by over-reading.

(4) The complete instrument is very portable, resembling closely a portable wireless set. It is rapidly connected to the circuit to be measured, and requires very little setting up or calibration.

(5) The cost of the usual glass pattern is much less than that of an electro-magnetic instrument.

(6) The indications are much more convenient to read and to scale off, rendering photography necessary only for record purposes.

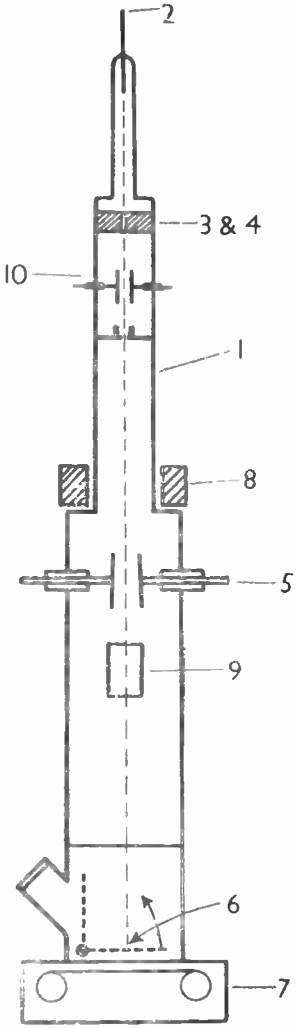


Fig. 1.—Cross-section diagram of the metal cathode ray oscillograph. The salient features are indicated by numbers, and each item is described below:

(1) *Metal tube.*
(2) *Cathode.*
(3) & (4) *gun: anode and diaphragm.*
(5) *X deflecting plates.*
(6) *Flourescent screen.*
(7) *Film holder.*
(8) *Focussing coil.*
(9) *Y Deflecting plates.*
(10) *Trapping plates.*

(7) The power demand is very low indeed, and thus the cathode ray oscillograph can be connected to even a very low current circuit without interfering with the existing circuit conditions. This is in many cases the most important advantage.

(8) There are other advantages of a minor description which will become apparent when the various applications are being considered in detail.

DESCRIPTION OF CATHODE RAY OSCILLOGRAPH.

There is no need to describe the "glass bottle" type to a gathering of radio engineers, who will be quite familiar with this form of instrument through its use in connection with television. The metal type will, however, be less well known, and a few words may be devoted to this pattern.

In general, the metal tube consists largely of a reproduction of the glass form on a somewhat larger scale, a common overall height being from 6 to 8 ft. Insulation is provided for the various "live" parts by means of porcelain bushes. It is generally designed for high voltages, such as 50 to 80 kV., and hence possesses a cold cathode. The almost invariable reason for its employment is, however, to enable a photographic record to be practicable when a single high speed sweep is employed, as in the tracing of lightning transients and the restriking voltages of large circuit breakers. This is accomplished by placing a photographic film inside the vacuum, where it can be directly reached by the cathode beam, in contradistinction to the method which has to be adopted with the glass type of instrument, of photographing the fluorescent screen with an ordinary lens camera.

A typical arrangement of metal tube is indicated in Fig. 1, where the various parts are shown more or less diagrammatically. The chief innovations as compared with the glass type are the pumping arrangements, which are not shown in the figure and are capable of evacuating the whole tube in from 10 to 30 minutes; the trapping arrangements, the focussing coil, and the internal film-holder or drum.

It is of interest to note that the suitability of the glass pattern for many industrial uses has been greatly enhanced owing to the rapid development called for by television, which has produced a tube with an extremely high writing speed, focussed by means of an electron lens, and capable of instantaneously varying its trace from complete blackness to full brilliance. The older gas-focussed, low voltage tube, however, finds many applications of a less exacting nature in industrial engineering.

APPLICATIONS OF CATHODE RAY TUBE.

The author proposes to divide the various applications of the cathode ray oscillograph into five classes, as follows:—

(1) Applications requiring only a single deflection, that is, employing only a single pair of deflectors.

(2) Differential applications, in which a similar voltage, current, capacity, pressure, etc., exerts its influence upon each pair of deflector plates, the two being balanced against each other, in very much the same way as weights are balanced in a pair of scales.

(3) Applications employing a repeating time base, in which a cyclic voltage (or current) is traced as many times as required for the purposes of observation or photography.

(4) Applications permitting only a single-sweep time base, such as lightning or circuit-breaking transients, where

difficulties of observation and photography are at a maximum.

(5) Applications in which the base is any quantity other than time, and therefore in which a curve is plotted connecting the variation of the one quantity resulting from the independent variation of another.

Various typical applications will be considered in detail below.

(1) Applications involving a single deflection:

The question might be asked why it is necessary to use an elaborate instrument like the cathode oscillograph when voltmeters and ammeters have been brought to such a high level of efficiency and performance. The answer is that although the performance of D.C. instruments, especially of the moving coil type, is adequate for nearly all purposes, this is not the case with regard to the A.C. instruments, and especially the A.C. voltmeter. Their chief drawback is the considerable amount of volt-amperes required to operate them, particularly when small current and voltages have to be recorded; but they also suffer through possessing an appreciable or excessive frequency error, and insufficient damping. As will already have been realised, the cathode oscillograph gives an almost perfect performance in all these respects.

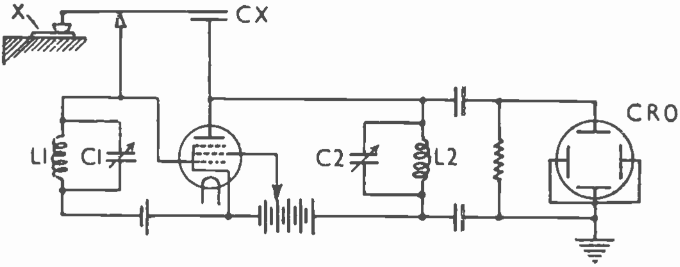


Fig. 2.—Circuit diagram showing the cathode ray tube as a thickness gauge.

It would therefore be expected that this application would be made chiefly for replacing an A.C. voltmeter, in those cases where high frequency or rapidly fluctuating waves have to be recorded. It is highly suitable, for example, for measuring the output from a mercury arc rectifier, while it is also employed for monitoring wireless broadcasts.

A specially interesting application is indicated in Fig. 2, in connection with the gauging of the thickness of metal or other sheets. The latter are passed under a rising and falling rod, the upper end of which can vary the spacing of a pair of condenser plates. These are connected between the grid and anode of an oscillating valve, directly varying the feedback and thus the amplitude of the output, which is indicated on the screen of the oscillograph tube.

(2) Differential Tests.

If two similar quantities are connected to the two plates respectively, the spot will be urged in the two directions at right angles with forces proportional to the magnitudes of the two quantities, and a direct comparison is thus afforded between them. If, for example, two sine waves are applied to the plates, and if these are in synchronism and of equal amplitude, then the figure traced in the screen will be a diagonal line inclined at an angle of 45° to either axis. If one of the waves is greater than the other, then the line will be inclined at a corresponding angle such that the tangent to the angle is equal to the ratio between the amplitudes. Further, if the two waves are not in step, then instead of a diagonal, an ellipse will be traced, becoming a circle when the phase difference is exactly 90°. From a knowledge of the ratio between the major and minor axes of the ellipse, the phase difference can be exactly estimated. This succession of figures will be recognised as being the simplest of the Lissajou's figures, corresponding to a frequency ratio of 1 to 1. One of the principal uses of the oscillograph employed in this way is therefore the comparison of phase angles.

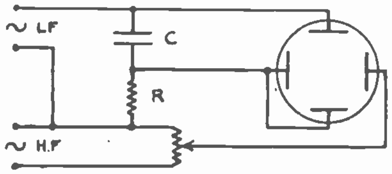
An ideal receiver for radio direction-finding is obtained by using the cathode oscillograph in this manner. If waves are being sent out from a given station, and are being received by two frame aerials at right angles to each other, one connected to each pair of deflectors, then a diagonal line will be recorded on the screen having an angle exactly proportional to the relative strengths of the two signals; that is, the diagonal line will point exactly in the direction of the transmitting station.

A synchroniser for paralleling alternators is constituted by connecting the busbar voltage to one pair of plates and the incoming machine to the other pair. When the machines are exactly in synchronism, the figure will have the form of a straight line which can be arranged to be exactly vertical or exactly horizontal. For any other relationship between the phase angles, the figure will either be an ellipse, a circle, or a straight line at right angles to the correct indication.

Frequencies may be compared by a simple extension of the phase difference rule, by making use of the higher order of Lissajou's figures that will be traced when the ratio between the frequencies is 2 to 1, 3 to 1, 5 to 2, or any other ratio. Although these figures at first sight appear to be complex, they will be found when one of the frequencies is so adjusted as to create a standing figure corresponding to the circle in the case of the 1 to 1 ratio, to follow a simple and uniform rule This is that if the number of loops along a horizontal axis is counted, and similarly the number of loops along one of the vertical axes, then the ratio between the frequencies is equal to the ratio between these numbers of loops.

Counting becomes somewhat difficult when one of the numbers in the ratio approaches double figures, and a slightly more complicated scheme of connections, shown in Fig. 3, renders the task easier by introducing a split phase characteristic. It will be seen that the upper source of sine waves, which is arranged to be that at the lower frequency, is connected to a condenser and resistance in series. This will feed a component of the frequency to each set of plates, but in quadrature with each other, causing the cross traverse to be elliptical or circular. The going and returning parts of the diagram are thus separated from each other and counting becomes correspondingly easier. The number of complete rings forms one number in the ratio, and the total number of loops forms the other.

Fig. 3.—
Diagram of a phase-splitting circuit for frequency comparison.



The power factor of condensers can be compared by connecting the sine wave source to the two condensers in series, and then connecting their terminals to the two sets of plates respectively. When the phase angles are equal, the diagonal line figure is given, and when the latter becomes an ellipse or circle, the rule already described holds good.

One of the most useful dicerential tests is effected when the input and output of an amplifier or a stage of a receiver set are compared, allowance being usually made for amplification by the inclusion of a potentiometer. When there is no distortion, a straight line figure is the result. Changes in phase angle are shown by a looped figure, and changes due to overloading are indicated by the bending over of the line at the upper or lower ends. It is usual to employ an oscillator to provide the signal, and by varying the frequency, tests can be made over the whole signal range.

(3) Applications requiring a repeating time base.

The most common applications of the cathode ray oscillograph are those employing a repeating time base, in which a cyclic change is caused to recur as often as is desired for purposes of observation or photography. These tests are not by any means the simplest, but they most closely resemble the use to which the electro-magnetic oscillograph is put, the base of which has practically always been derived from a rotating drum or cine film. It is one of the great advantages of the cathode type oscillograph that so many different kinds of time base are available. A linear time base most closely corresponds with electro-magnetic oscillograph practice, and nearly all commercial cathode oscillographs incorporate such an arrangement. For many purposes, however, it is an advantage to have the exponential time base given by the charge or discharge of a condenser through a plain resistance, since a number of transients are most conveniently recorded by a means which will extend the scale of the front and compress the tail.

There are naturally many kinds of test which can be carried out by means of the repeating time base. Probably the most familiar are those for the determination of the wave form of electrical machines, transformer, and rectifiers. Even D.C. generators are tested in this manner, in order to ascertain the magnitude of ripples due to commutator and slots, information which is of great importance for such purposes as the supply of telephone exchanges. The existence of harmonics in the output of alternators is a further example, and the same information is required with regard to transformers. Several different kinds of tests are made on mercury arc rectilers, including the estimation of the arc drop and arc losses, and the wave form. An interesting example of the latter is shown in Fig. 4, in which the lowest of the oscillograms gives the shape of the output as it normally is; although this figure should be understood as being merely the ripple on a direct current, the D.C. component being suppressed by the amplifier of the oscillograph. This current would actually be smooth enough for most purposes, but when greater steadiness is required, filters are added consisting of acceptor circuits which can remove unwanted harmonics. Curve A contains the 6th, 12th, 18, 24th . . . harmonics, and in the upper

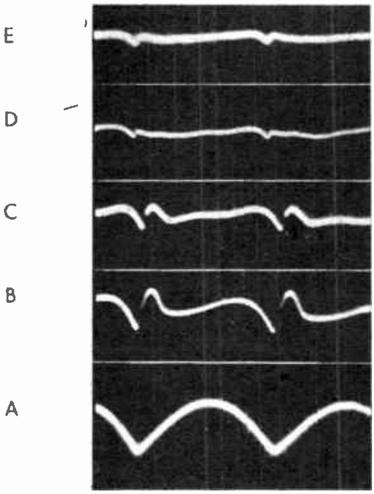


Fig. 4—Oscillograms showing the effect of ripple filters. Trace A shows the waveform at the output terminals of a mercury arc rectifier, while traces B to E show how harmonics of progressively higher orders are attenuated by the filters.

curves these harmonics have been removed one by one. For example, the 6th has been removed in Curve B, the 6th and 12th in Curve C, and so on.

The input and output of stages in a radio set can be compared by this method by arranging a changeover switch so that the input curve is traced first and the output immediately afterwards. Alternatively, the two can be traced on the one diagram simultaneously by means of a double-beam type of oscillograph.

Rapid fluctuations in a number of quantities other than electrical can be traced in this way, of which space will only permit reference to two. Pressure fluctuations, such as those imposed on the head of a ferro-concrete pile, can be recorded by embedding a piezo-electric crystal pick-up in the material, while wind and gas velocities can be similarly recorded, so sensitively as to include the effect of very rapid turbulence, by connecting the deflecting plates to two small pointed electrodes having a very short gap between them, across which a glow discharge is maintained by means of a constant D.C., the wind velocity varying the voltage drop across the electrodes.

Particularly interesting forms of oscillograph set that have been designed quite recently are those which simulate the effect of single-sweep transients, by generating square-fronted waves on a small scale and applying them repeatedly to the circuit under examination. By this means, both observation and photography are greatly simplified. Examples are the recurrent surge oscillograph and the restriking voltage indicator due to K. R. J. Wilkinson, which can simulate the effects of lightning surges, and of restriking voltage transients from a large circuit breaker, respectively.

(4) Single-sweep Transients.

It is in cases where only a single discharge or other single transient has to be recorded that the metal tube oscillograph finds its usual application. There are two main types of phenomena that are recorded in this way. The first of these is the lightning discharge, derived either from nature, or, more usually, from an artificial lightning generator. Such records are essential in connection with testing and research upon lightning arresters; while they are also made upon apparatus, such as transformers or cables, in order to study the distribution of the surge in various parts of the conductors.

The second type of transient is the high frequency voltage that occurs at the terminals of a large circuit breaker at the instant when it has ruptured a short circuit. The question as to whether the arc will be restruck or whether the gap has become sufficiently de-ionised during the zero pause to prevent restriking depends largely upon the rate of rise of this restriking voltage. Since it oscillates at the natural frequency of the circuit, which may be of the order of ten thousand to a hundred thousand cycles per second, it leaves no record whatever upon the electro-magnetic oscillogram, and a sensitive cathode ray instrument is essential for obtaining this information. A typical record, obtained by means of a metal tube oscillograph, is shown in Fig. 5, where the nearly straight curves are the normal 50-cycle supply voltage, and the high frequency transient is the voltage oscillation where the arc is finally prevented from restriking by the increased resistance of the arc space.

(5) Applications involving bases other than time.

The last group is of considerable importance, as it includes the recording of tests that were beyond the powers of the electro-magnetic oscillograph. Many of these are tests which are usually carried out by the slow process of plotting a series of points connecting the change in one quantity with a change in another, and which may now be carried out by means of the cathode oscillograph at greatly increased convenience and in only a fraction of the former time.

Curves connecting the voltage and current are among the most usual test relationships that are required, and these present no difficulty. Resonance, which occurs in a circuit when the voltage and current are in synchronism, can be indicated by the Lissajou's figure becoming a diagonal straight line. Valve characteristics, such as those of the tetrode or pentode, connecting the anode current with anode volts, can be instantaneously traced out with varying grid bias; while grid volts / anode current curves can be similarly plotted. The ability to ascertain immediately the effect of various changes is one of the great advantages of the oscillograph method of test, as is also the ability to test a large consignment of valves in succession, in only two or three seconds for each valve.

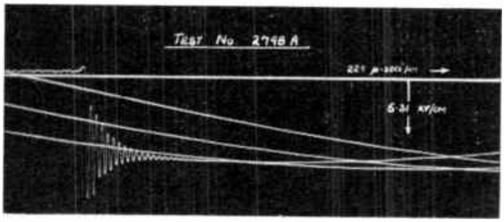


Fig. 5.—Photographic record, made on the film in one of the large metal cathode ray tubes, as a circuit breaker opens. It represents the electrical disturbance at the circuit breaker terminals.

Hysteresis (B/H) curves for magnetic materials can be obtained with similar rapidity, by connecting one pair of plates to a shunt in the exciting current circuit, and the other pair to a secondary winding for measuring the flux. This curve is ordinarily a very troublesome one to obtain, but by the method described it becomes so simple that it may be used as a routine test for many samples of iron in succession. A typical record is given in Fig. 6.

One of the most interesting examples of this type of test is the electronic steam engine indicator, in which the fluctuating pressures in the engine cylinder are recorded by the agency of a piezo carbon resistance, or variable, capacity pick-up, the longitudinal travel being obtained by means of a cam type shutter and photo-electric cell mounted at the end of the engine shaft.

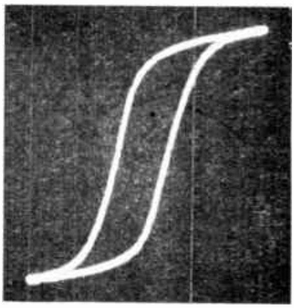


Fig. 6.—Hysteresis curve, photographed directly from the screen of a glass cathode ray tube. The apparent irregularity of the edges of the trace is due to the lines of a calibration screen fitted to the front of the tube.

Conclusion.

The above examples are naturally only representatives of what the cathode ray oscillograph has done and is doing to facilitate testing and research work in industrial engineering. Great improvements are being carried out in all types of cathode oscillograph at the present time, and new uses are continually being found for it. There is no doubt that its importance will continue to increase in the near future.

Note.

During the course of the above remarks, the lecturer showed about 45 slides illustrating the practical use of the cathode ray oscillograph, and gave a demonstration showing its mode of use and indicating the convenience and rapidity with which its determinations are made; about eight representative tests from Classes 1, 2, 3 and 5 being carried out.

An extension of this paper was given by Dr. Wilson at a meeting of the London Section of the Institution on January 10th, 1941.

The

British Institution of Radio Engineers

(Founded in 1925 as The Institute of Wireless Technology. Incorporated 1932.)

PROCEEDINGS.

APPLICANTS FOR MEMBERSHIP.

Since the September-October issue of the JOURNAL there has been two meetings of the Membership Committee and one meeting of the General Council at which the election of the following candidates for membership have been confirmed.

The following were elected on the 25th November, 1941 :—

Graham, F. N. Knewstub	Amersham, Bucks.	—Associate Member*
Frank J. Newland ...	Highbury, N.5.	—Associate Member
William P. Rowley ...	East Sheen, S.W.14	—Associate Member†
Clifford Brent	Weston-super-Mare	—Associate
Ernest G. P. Chalken, B.Sc.	Isleworth, Surrey	—Associate
John C. G. Field, B.Sc. (Hons.)	Haslemere, Surrey	—Associate
Eric G. Sugars, Grad.I.E.E.	London, N.W.4.	—Associate
Charles A. Ward ...	Huddersfield	—Associate
Charles H. Wignall ...	Sunderland	—Associate

† *Transferred from Graduate.* * *Transferred from Associate.*

The following were elected on the 30th December, 1941 :—

Edward Cattanes	Cockfosters	—Corporate Member
John Charles George Gilbert	Worcester Park	—Corporate Member*
Henry Alexander Hartley	Isleworth	—Corporate Member
Walter William Smith, B.Sc.(Hons.), A.M.I.E.E.	Solihull	—Corporate Member
Henry Cameron Barnett	Potters Bar	—Associate Member
Patrick Joseph Best ...	Preston	—Associate Member
Frederick Lonsdale Channell	London, N.W.1.	—Associate Member†
Redvers Hector Baden-Powell Chappell ...	North Finchley	—Associate Member†
Frank Edward Collis ...	Buckhurst Hill	—Associate Member
George Basil Harding ...	Sleaford	—Associate Member
Edward Hedgecock ...	Sutton Coldfield	—Associate Member
Walter Wilfred McLane	Otley	—Associate Member
Sydney Lloyd Robinson ...	Watford	—Associate Member
John Leslie Woods ...	Cranwell Village	—Associate Member
Donald Sidney John Bushnell	Croydon	—Associate
William Dyson Bottomley	Troon, Ayrshire	—Associate
Edward George Hamer ...	Willenhall	—Associate
Howell Samuel Hughes ...	Manchester	—Associate

* *Transferred from Associate Membership.*

† *Transferred from Associate.*

The following were elected on the 27th January, 1942:—

Stanley George Button ...	Bradford	—Associate Member
Herbert Arthur Cheadle...	Greenford	—Associate Member
Kenneth Arthur Headley Adams, B.Sc. ...	South Africa	—Associate
John Andrew Currie ...	Birmingham	—Associate
Henry George Manfield...	Inverness	—Associate
Cecil Strickland	Huddersfield	—Associate
Donald Charles Watson ...	Sleaford	—Associate

The following Studentship Registration have also been confirmed:—

Edmund Neil Brookes	Barnsley.
Eric Wilfred Hayden Browne	Folkestone.
Francis Edward Castleman	Northwood.
Nathaniel Ceen	Dollis Hill.
Benjamin Chippendale	Hebden Bridge.
John Westacott Davis	Henleaze.
Alan John Edwards	Solihull.
Oscar N. Ehrenfest, Ph.D.	Cromford, Matlock.
Walter Farrar	Horsham.
Fred William Gair	Colindale.
Cecil Ernest MacLeod Iles	Whitchurch.
Fred Marsden	Goldthorpe.
Walter Thomas Clayton Mayne	Kettering.
Thomas Mewes	Newcastle-on-Tyne.
Charles Ray Morris	Northumberland.
John Nolan	Swindon.
Raymond Oliver, B.Sc.	Swindon.
Ernest Frank Piper, A.M.I.E.E.	West Hove.
Ronald Harry Price	Strawberry Hill.
Christian Frederick Cable Scott	Croydon.
Joseph Horace Whaile	Leamore.
Tor Stuland	Liverpool.
Charles William Sullivan	Wirral.

RESIGNATIONS.

The Council have been compelled to assume, with regret, the following resignations:—

Young, Henry, W.	Tenby, S. Wales	E.	July, 1938	—Associate Member
Cheney, Harold, J.	Birmingham	E.	July, 1933	—Associate
Allen, Albert T.	Liverpool	E.	August, 1935	—Student
Bennett, C. R.	Cranwell	E.	March, 1938	—Student
Bracher, Archer S.	Plympton, Devon.	E.	October, 1935	—Student
Cossey, J.	Portsmouth	E.	November, 1937	—Student
Drake, Herbert W.	Chelmsford	E.	September, 1934	—Student
Fraser, William	Cricklewood	E.	March, 1938	—Student
Hastings, William	West Hartlepool	E.	November, 1938	—Student
Higham, John A.	St. Helens, Lancs.	E.	April, 1937	—Student
Mellinger, M. A.	London, N.W.8.	E.	November, 1937	—Student
Midson, J. W.	Bexleyheath, Kent	E.	October, 1937	—Student
Needham, Albert G.	Winewall, Lancs.	E.	November, 1937	—Student
Roberts, William A.	Droitwich	E.	December, 1937	—Student

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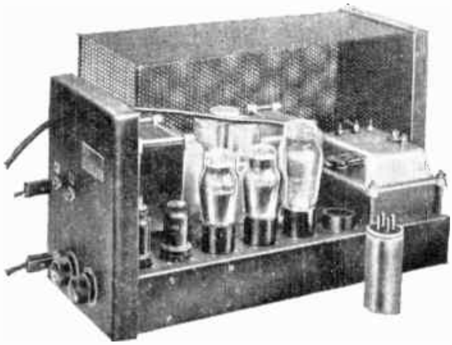

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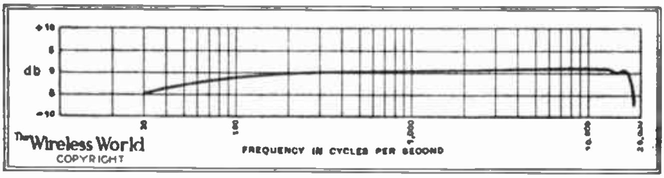

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