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"To promote the advancement of radio, electronics and kindred subjects by the exchange of information in these branches of engineering."
(from the objects of the Institution)

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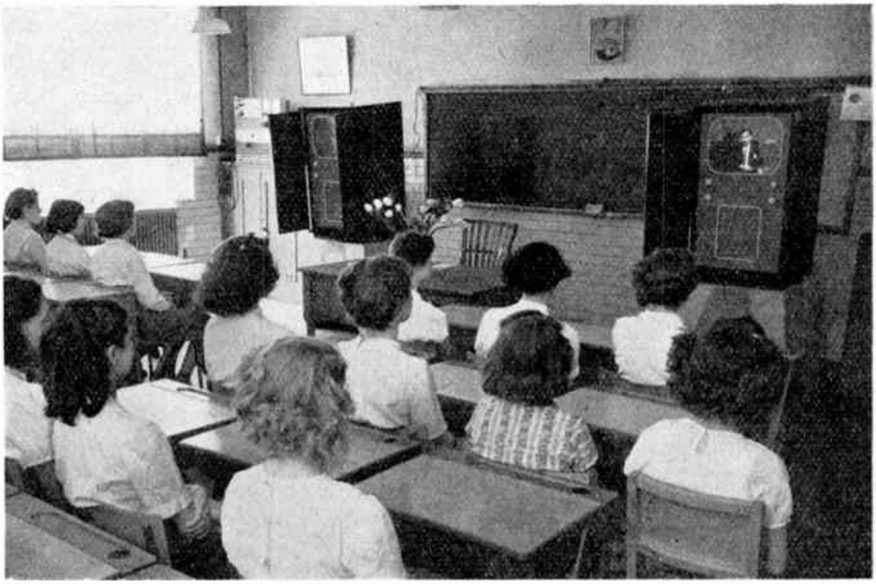
AN IMPORTANT CONTRIBUTION TO EDUCATION

On Monday, May 5th, the British Broadcasting Corporation broadcast the first television programme for schools. The programmes are being received in six Middlesex Secondary Schools and nearly 1,000 children are seeing daily transmissions. This present series of transmissions will prepare the way for a bigger experiment later on, planned to throw light on the wider technical and educational problems of a schools television service.

The programmes deal with such subjects as science, current affairs, travel and the industrial scene. Their production has required a team effort in which engineers and educationalists have collaborated. An outstanding example of co-operation is that the schools have been equipped with apparatus lent free of charge by a number of radio manufacturers.

For the present, the programmes are broadcast from Alexandra Palace on a special wavelength with the sound conveyed to the selected schools by land line. Some of the programmes are for children of 11 to 13, some for the 13 to 15 age group, and others for the wider age range of 11 to 15. Obviously, the scheme is capable of wider utilisation and can internationally be a potent force in the broader education of future generations.



Photograph by courtesy of the B.B.C.

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TECHNICAL COMMITTEE REPRESENTATIVES

John A. Sargrove, who was born in London on May 23rd, 1906, received his technical education at the Regent Street Polytechnic, London.

After several years in the drawing offices of various electrical and radio manufacturers, Mr. Sargrove was employed by Tungsram Electric Lamps, Ltd., in 1930 on patents research. He subsequently joined the development department and in 1933 was appointed Chief Engineer of the Technical Department. In 1940 he became Chief Engineer of Electro-Physical Laboratories. Sargrove Electronics, Ltd., of which he is managing director, was formed in 1942.

Mr. Sargrove is well known to all radio engineers for the electronic circuit-making equipment which he designed. This equipment was described in his paper "New Methods of Radio Production," published in the January 1947 issue of the *Journal*, and for which he was awarded the Clerk Maxwell Premium. He is the author of three other papers in the *Journal* dealing with Photoelectric Cells, and Valve Theory.

Elected a Full Member of the Institution in July 1939, Mr. Sargrove served as a Member of the Council from 1941 to 1943, and as Chairman of the Papers Committee from 1940 to 1942. He has been a member of the Technical Committee since 1945 and represented the Institution on committees of the British Standards Institution between 1944 and 1947.

Frederick George Diver was born at Holmwood, Surrey, in 1904, and was first employed by the Low Engineering Co., Ltd., at Feltham, Middlesex, as engineer in charge of experimental radio reception and he was later associated with the Marconi International Marine Company.

In March, 1928, Mr. Diver joined his present company, McMichael Radio, Ltd., as Chief of Test, and in that capacity was responsible for test, inspection and test gear design until 1939. He was then appointed Chief Engineer in charge of all design, development and test engineering, and from January 1946 to the present time has held that position in the Equipment Division.

Mr. Diver was elected a Member of the Institution in 1943 and has served on the Technical Committee since 1947. He was jointly responsible with Mr. H. E. Drew (Member), for the preparation of the Committee's report on "Good Engineering Practice," published in the January 1951 issue of the *Journal*.

Geoffrey Wooldridge was born on March 3rd 1920, at Stourbridge, Worcestershire. He obtained a degree in Electrical Engineering with honours in Communication Engineering at Birmingham University in 1940, and shortly afterwards joined the Air Defence Experimental Establishment of the Ministry of Supply as a research physicist. During the war he was engaged on research and development of radar and allied techniques.

In June 1945 he was appointed to take charge of the Airborne Forces Section of the Operational Research Group of the Ministry of Supply, a position he held until 1951 when he transferred to his present post on the staff of the Scientific Adviser to the Army Council. He now holds the rank of Senior Scientific Officer.

Mr. Wooldridge joined the Institution as an Associate in 1940, and was transferred to Associate Membership in 1947. He has been a member of the Education and Examinations Committee since 1948, and in 1951 he was elected to Council.

In addition Mr. Wooldridge has served on Technical Committee ELE/9 of the British Standards Institution and on its various sub-committees dealing with Nomenclature and Symbols as a representative of the Brit.I.R.E. Technical Committee since 1947. He contributed a paper on waveguides to the *Journal* in 1942.

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JOURNAL OF THE BRITISH INSTITUTION OF RADIO ENGINEERS

MICROGROOVE RECORDING AND REPRODUCTION*

by

E. D. Parchment (*Associate*)†

A Paper presented at the Sixth Session of the 1951 *Radio Convention on September 4th, at Earls Court, London.*

SUMMARY

Many of the problems discussed in this paper will be well known to recording engineers, as they are basic problems. In microgroove recording, with its reduction in turntable speed, together with the diminished groove size, these difficulties are disproportionately magnified. The paper deals only with those points which are of prime interest, and no mention is made of the complexities arising in processing.

1. Mechanical Considerations

Probably the best-known (and perhaps the most debated) function of recording equipment is the frequency characteristic. Before discussing this point, it is proposed to review, in the light of modern developments, some of the mechanical problems involved. Similar problems confront the designer of reproducing equipment, added to which is the consideration of cost. The speed of 78-r.p.m. records coupled with the groove dimensions tends to simplify the mechanical requirements. The first and obvious steps towards a longer playing time are the reduction of turntable speed and an increase in the number of grooves cut per inch. The main difficulty encountered with a reduction of turntable r.p.m. is that speed fluctuations usually occur due to the rapid decrease of kinetic energy. This was pointed out by West[1] in a recent article. These deviations from mean speed are commonly termed "flutter" or "wow," depending on their cyclic rate.

An increase of the number of grooves per inch necessitates a smaller groove to enable the groove/land ratio to be maintained, and a lower average recording level. The latter, as might be expected, leads to the consideration of the mechanical disturbances which may be transmitted to the turntable and to the recording head.

It is fortunate in both respects that existing professional equipment, as developed over many years, has been designed to combat such effects. Recording turntables are commonly of considerable mass, of the order of 40-70 lb., mounted on bearings designed to give a minimum of friction. As shown in the electrical analogue, Fig. 1, the power transmission is through a compliance C incorporated in the drive shaft, followed by a damped compliance, C_1R, between this and the turntable. The value of the compliance C is normally of the order of four to five times that of C_1. The filter prevents instantaneous drive side disturbances from reaching the turntable in the form of vibration or flutter, while the turntable inertial energy militates against the effects of variable cutting load. A similar damped compliance filter is attached to the recording head.

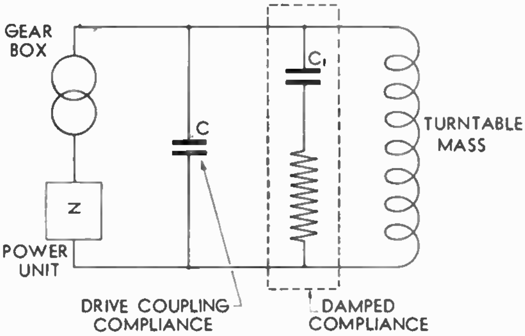

Fig. 1.—Electrical analogue of mechanical filter used in recording machine drives.

For home use it becomes impossible to resort to the use of complex mechanical filters; the cost would be prohibitive, to say nothing of the dimensional and weight aspects. Extremely good results are obtainable by using "rim-drive" systems, provided that the fundamental points are not neglected. Firstly, the motor must have the lowest possible inherent vibration; secondly, all bearings must be finished to very close tolerances to avoid cyclic frictional changes; thirdly, all driving surfaces must be concentric to close limits.

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* Manuscript received August 23rd, 1951.
† The Decca Record Co., Ltd.
U.D.C. No. 621.395.625.2.

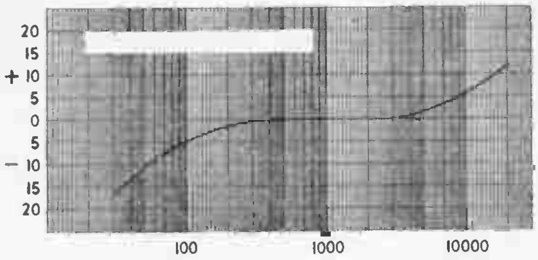

Fig. 2.—Decca 78-r.p.m. characteristics.

2. Recording Characteristics

It has been common in English recording to use a crossover frequency between the constant amplitude and constant velocity sections of the curve, at about 250 c/s. As in the constant velocity region the recording stylus excursions increase with a decrease in frequency, maximum amplitudes occur immediately above the crossover point. In addition, the effect is increased by the naturally high energy content of speech and music in this part of the spectrum. A curve of this type is shown in Fig. 2.

To diminish this effect, American recordings generally employ a characteristic similar to that of N.A.B., as shown in Fig. 3 (upper curve is for vertical and lower for lateral recording), where it can be seen considerable decrease in amplitude is achieved by resorting to the simple expedient of raising the crossover frequency.

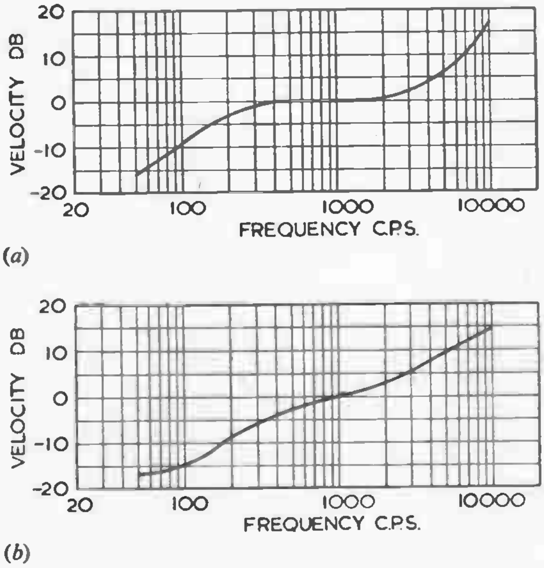

Fig. 3.—American N.A.B. characteristics: (a) for vertical recording: (b) for lateral recording.

In all the recording characteristics shown, H.F. pre-emphasis is incorporated. This is a somewhat controversial subject. It can, of course, be argued that pre-emphasis increases tracing distortion. Although this is theoretically true, it does appear to resolve itself into a matter of degree, namely, permissible distortion weighed against the practical advantages. The latter are fairly obvious. Pre-emphasis allows a subsequent de-emphasis over a portion of the frequency range where surface noise is an unpleasant problem, also it is helpful when used in conjunction with the cheaper or more popular forms of reproducers.

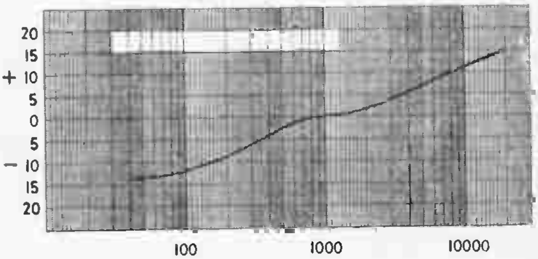

Fig. 4.—Decca 33⅓-r.p.m. characteristics.

In microgroove recording where it is common to use 250 or more grooves per inch, to avoid excessive stylus amplitudes it becomes a practical necessity to use a high crossover frequency. The curve, as shown in Fig. 4, is, in fact, very similar to that of N.A.B., the main difference being the extreme L.F. end which is maintained at a slightly higher level. This enables the signal level to be kept sufficiently high to avoid some of the difficulties caused by "motor rumble" in reproduction. Again, this characteristic uses H.F. pre-emphasis. In the original American characteristic this was approximately 6 db per octave. The first Decca microgroove records, as released in the United States, were cut with an almost exactly similar characteristic.

However, as mentioned before, the degree of pre-emphasis must be considered in relation to the permissible tracing distortion. The present characteristic incorporates a modified pre-emphasis curve in such a manner that the value is + 11 db at 10,000 c/s, as against the American figure of + 16 db.

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An additional factor which must also be taken into account is that of the average recording level, which in the case of microgroove is 6-10 db lower than for 78 r.p.m. Dynamic range may be maintained the same on microgroove records as on 78 r.p.m., firstly, due to maintenance of a virtually constant amplitude over the frequency range, and, secondly, pianissimi may be allowed to fall to lower levels, due to the lower suface noise. The latter is achieved by the additive effects of pre-emphasis, and the use of vinyl co-polymers in place of shellac compounds.

3. Cutting Problems

Before further discussion of the tracing distortion question, there is an intermediate problem concerning the actual cutting function of the recording stylus. With the widespread use of Nitro-cellulose lacquers, it was found that considerable surface noise improvement could be effected by modifying the cutting stylus with what is generally known as a "burnishing facet." As shown in Fig. 5, these facets entail the virtual removal of the sharp cutting edges. The sketch shows only the basic idea, which is much modified in practice.

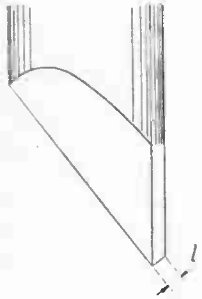

Fig. 5.—Cutting stylus with burnishing facet for nitro-cellulose lacquers.

This device has been well covered elsewhere,[2] and will only be dealt with here in its relation to frequency response. The effect was clearly described by Le Bel.[3] Briefly, the facet imposes a varying impedance to lateral motion of the recording stylus, causing a H.F. loss, which is the function of recording diameter. Le Bel describes the problem in terms of burnishing facet length (as shown in Fig. 5) versus the recorded wavelength:

$$\frac{l}{\lambda}$$

therefore, if $\lambda = \frac{\pi D}{f} n$

the ratio $\frac{l}{\lambda} = \frac{fl}{\pi D n}$

where D = diameter of recording

l = length of burnishing facet

n = revolutions per second.

This effect can be shown quite readily by cutting a H.F. from start to finish on a recording blank where it can be seen that the Buchman Meyer pattern displays an obvious loss on small recorded diameters. Although this loss can be kept reasonably small at 78 r.p.m. by careful production of the facet, its effect on microgroove becomes severe. There are three methods by which this problem may be overcome. Firstly, the hot stylus method described by Bachman.[4] This utilizes a small coil attached to the cutting point in close proximity to the tip, through which a current is passed raising the stylus to a temperature at which the cellulose lacquer softens during cutting.

The second method developed by C. E. Watts, although simpler in concept, appears equally efficacious. This method is the inverse of the hot stylus technique. A radiant heat lamp is suspended over the recording turntable, thereby raising the temperature of the lacquer and producing an effect analogous to that of the hot stylus.

The third method is the oldest used in the industry, namely, the use of wax. As it is unnecessary to employ burnishing facets on wax styli, the problem no longer exists. There are other advantages associated with the use of wax, for example, the surface flatness may be maintained with great accuracy. In addition, with the absence of "pinholes" and other surface defects, processing is considerably facilitated.

4. Tracing Distortion

As tracing distortion has been thoroughly covered by numerous investigators, only a brief description will be given of the basic theory. As the cutting stylus is a V-shaped device as against the hemispherical nature of the reproducing point, distortion occurs by the failure of the latter point correctly to trace the recorded wave shape. As it is somewhat clearer to show this distortion in vertical recording as opposed to lateral, the vertical will be shown first. In Fig. 6 the dotted line indicates the reproducer trace, plotted against the cosine curve of a vertically

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cut wave. Pierce and Hunt[5] termed the reproduced curve a "poid."

If x and y are the co-ordinates of the cosine curve and ξ and η the co-ordinates of the centre of the tracing circle (ξ is the forward travel of the stylus along the groove), the cosine curve is given by:—

$$y = a \cos \frac{2\pi x}{\lambda} = a \cos kx$$

now $\xi = x + r \sin \theta$

and $\eta = y + r \cos \theta = a \cos kx + r \cos \theta$

where $-\tan \theta = -ka \sin kx$

Eliminating θ between the last three equations gives

$$\xi = x + \frac{kar \sin kx}{\sqrt{1 + k^2a^2 \sin^2 kx}}$$

$$\eta = a \cos kx + \frac{r}{\sqrt{1 + k^2a^2 \sin^2 kx}}$$

as the parametric equations of the poid with x as the parameter. As pointed out by most of the writers on the subject, the straightforward method of calculating the harmonic content of the poid would be the elimination of x between these two equations, and expressing η as a Fourier expansion in ξ, in which the co-efficients of the trigonometrical terms were exact expressions. It is also pointed out that this is a very difficult mathematical operation.

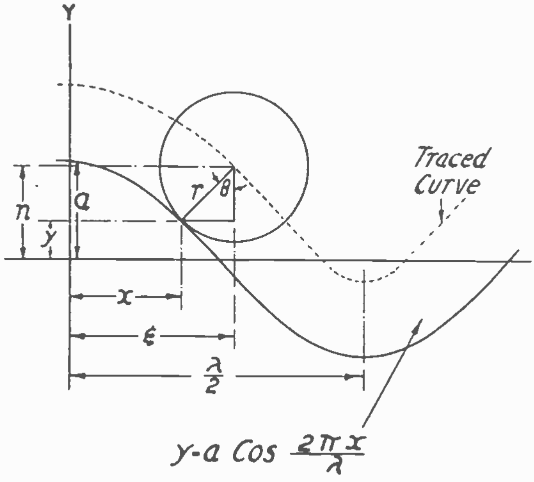

Fig. 6. The reproducer trace.

Pierce and Hunt used an approximate analysis which gives the numerical values of the co-efficients in the series, and, therefore, the harmonic components with adequate accuracy. Expressed as a series:

$$\eta = a_1 \cos k\xi + a_2 \cos 2k\xi + a_3 \cos 3k\xi + \dots\dots$$

In the case of vertical recording, none of the co-efficients of the series is zero, so the stylus motion contains both odd and even harmonics. Lateral analysis is more complex, and Pierce and Hunt adopted the expedient of treating the motions imparted to the stylus by the two groove walls separately, and then adding them in proper phase. This shows that, in lateral reproduction, even harmonics are absent in horizontal motion, but are present in the vertical motion; the latter motion being imparted by the differential groove width caused by modulation and termed "pinch effect."

Expressed mathematically:—

$$\eta_L = b_1 \cos k\xi + b_2 \cos 3k\xi + \dots\dots$$

$$\eta_V = c_1 \cos 2k\xi + c_2 \cos 4k\xi + \dots\dots$$

where η_L and η_V = horizontal and vertical components respectively.

As the shape of the traced curve depends on the relative and not the actual dimensions, the shape can be specified by the values of the ratios a/λ and r/λ where a is the amplitude of the wave form, λ is the wavelength and r the stylus tip radius.

It must be stated that the analysis assumes contact at all times between the stylus and the groove wall, that the stylus is, in fact, supported by the walls of the groove and not the bottom, that no deformation occurs in the groove walls. However, experimental results have proved fairly close agreement between calculated and measured distortion. A later paper by Corrington[6] emphasizes that, in the case of large amounts of distortion, the Pierce and Hunt analysis using points every 30 deg. of the cycle is not sufficiently accurate.

Pierce and Hunt published a graph by means of which the percentage of total harmonic content may be ascertained as a function of ka and kr. Using this information as a basis, the relative figures for 78-, 45- and 33⅓-r.p.m. records have been plotted versus playing time in Fig. 7. It is readily discernible that both forms of microgroove recording exhibit lower inherent distortion in comparison with 78 r.p.m., due to the favourable relative dimensions ka, kr, in the

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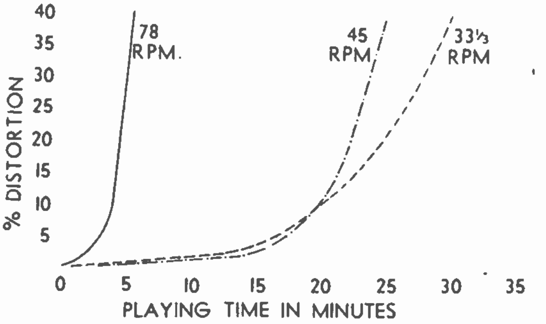

Fig. 7.—Related distortion percentages for 78, 45 *and* 33⅓ *r.p.m.*

former. However, it must be pointed out that this improvement is not fully realizable as high frequencies on microgroove records approach velocity levels comparable with those on standard records.

Numerous references have been made, by other writers on this subject, to the favourable energy distribution in speech and music. There can be no doubt of this, and it can be shown theoretically that, if this were not so, even a constant velocity characteristic would otherwise produce an intolerable amount of distortion.

To support this statement, it was decided to photograph the energy levels in the audio spectrum under dynamic conditions. There was available an instrument designed and built by Jaquess[7] in 1947 to give a panoramic display of the audio spectrum from 0-20 kc/s. Into this was fed the signal from a pick-up giving a "flat" response from 250 c/s upwards (no "bass" correction network) reproducing a standard shellac record. The energy levels shown include those of random noise.

Time exposures of 1½ and 2 minutes, respectively, were given in order to produce photographs showing average levels. These are shown in Fig. 8. It is not intended to attempt an exact evaluation at this stage, the photographs are shown only as a matter of interest. The author hopes that it may be possible to continue investigations, using this and other methods of analysis.

5. Pick-ups

The reduced groove size, plus the change in record material, although not presenting basically new problems, greatly accentuate those which exist. The H.F. resonance of a pick-up is a function of the mass of the moving parts and the added "stiffness" of the record material. In addition, the latter is affected by the stylus-tip radius and the downward pressure. Assuming perfect point contact between stylus and groove wall, the point pressure must be infinite, therefore the groove material deforms until the bearing area dimension is large enough for the forces to reach equilibrium. If the tip radius is reduced from 0·0025 in. to 0·001 in., the point pressure reduced in similar manner, and the record material compliance is increased, it follows that the pick-up resonant frequency will be lowered. For example, a pick-up having a resonance of 15,000 c/s on standard shellac records resonated at 10,000 c/s on microgroove.

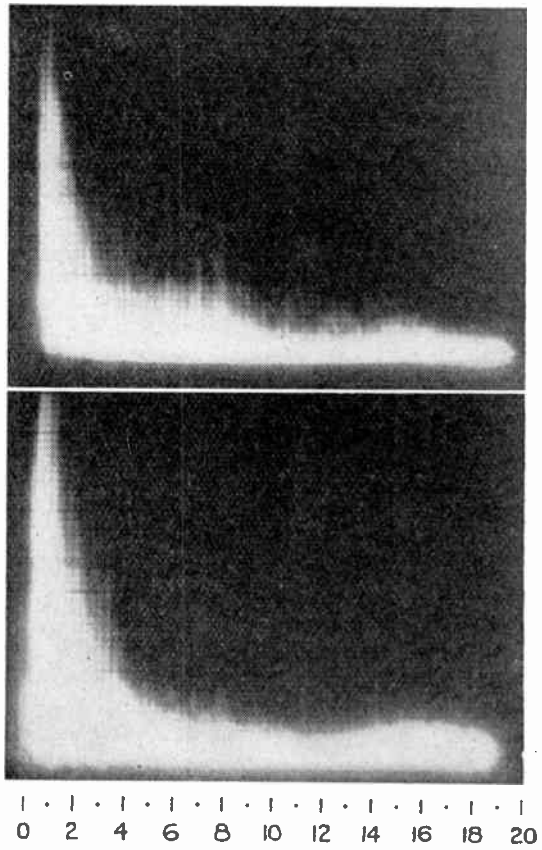

Fig. 8.—Audio spectra, 0-20 *kc/s, taken from standard records. Top—2nd side of "Danse Macabre." Bottom—1st side of "Beethoven 5th Symphony."*

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With regard to the necessary pick-up stylus compliance, an approximation may be arrived at by assuming a maximum recording amplitude A. As it is usual to employ an included angle of approximately 90 deg., the vertical force F_V which tends to force the stylus out of the groove is equal to the lateral force F_L. This lateral force has a component F_S, must overcome the lateral mechanical impedance of the stylus point. As the stylus is stiffness controlled at low frequencies, where most tracking problems occur:—

$$F_V = F_L = F_S = \frac{A_{max}}{C_S}$$

where $C_S =$ stylus compliance.

From this $F_v = \frac{A_{max}}{C_S}$ or $C_S = \frac{A_{max}}{F_V}$

If A_{max} is 0·001 in. and point pressure is 8 gm.

$$C_S = \frac{0{\cdot}001 \times 2{\cdot}54}{8 \times 981} = 0{\cdot}32 \times 10^{-6} \text{cm/dyne}$$

For 78 r.p.m., if A_{max} is 0·002 in. and the point pressure is 20 gm.,

$$C_S = \frac{0{\cdot}002 \times 2{\cdot}54}{20 \times 981} = 0{\cdot}26 \times 10^{-6} \text{cm/dyne}$$

As these are only minimum values, it follows that the stylus compliance should be at least twice in both cases. It is not intended to imply that this is the only pick-up requirement, but it is certainly an essential consideration. In practice, the mass/compliance relationship determines the mechanical impedance, and unless due attention is paid to this the impedance may become excessive at the extremes of the frequency range.

As an example of current pick-up design, the Decca magnetic pick-up gives the following figures:—

Compliance	$1{\cdot}1 \times 10^{-6}$ cm/dyne
Impedance at arm resonance (i.e. 25 c/s)	17,000 mechanical ohms

The general design of this pick-up is now well known, and requires no detailed description, although attention might be drawn to the armature which is constructed as a tapered tube, the intention being to avoid modes of vibration caused by the armature "flexing."

With the introduction of microgroove, it was necessary to reduce the armature mass and the resonances of this modified version are:—

78 r.p.m.	18-19,000 c/s
33⅓ r.p.m.	14-15,000 c/s

(See Fig. 9.)

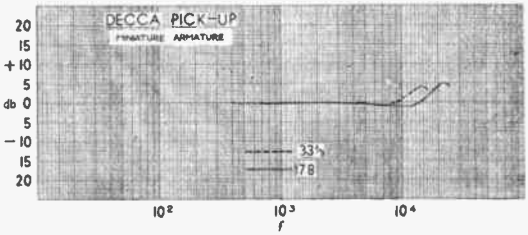

Fig. 9. *Frequency characteristic for miniature armature.*

6. Acknowledgments

The author wishes to express his thanks to Mr. N. C. Mordaunt, whose work is well known in the audio field, for his kind co-operation.

In addition, the author's thanks are due to Mr. H. F. Schwarz, Technical Director of the Decca Record Co., for permission to publish this paper, and for his helpful advice and criticism; to Mr. D. G. Jaquess for the preparation of the tracing distortion curves, and to Mr. Mr. D. J. W. Segrove for the wave analyser photographs.

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EXHIBITION REPORTS

Physical Society's Exhibition

The 36th Exhibition of Scientific Instruments and Apparatus arranged by the Physical Society was held in Imperial College, London, from April 3rd to 8th, and was, as usual, well supported. For the benefit of members who have not attended this exhibition it may be stated that it can be divided into two sections: displays of research apparatus and experiments by university, Government and industrial research laboratories and manufacturers' stands showing new instruments. The exhibition is specifically not a trade show and the great majority of the exhibits have not been shown in previous years.

Electronic exhibits by research laboratories included prototype computing equipment such as the magnetic drum stores for digital computers demonstrated by the Telecommunications Research Establishment. One type provided storage of over 1,700,000 binary digits with a mean access time of about 1 sec. The other type aims at a high-frequency response (about ½ Mc/s) and is stated to have the storage capacity of 64 ultrasonic mercury tanks each containing 1,024 digits.

There were a number of demonstrations of microwave equipment, both for communication and nucleonic applications. These included apparatus shown by Marconi, working in the 9-mm band and demonstrating the Doppler effect, Rayleigh range and the effectiveness of crossed polarization for duplex working.

A number of exhibitors showed electronic control equipment for industry and in particular apparatus for use in the textile industry to maintain a continuous check on the thickness of yarn or on its tension. The application of ultrasonic waves to the testing of metals is now well established, and several instruments were on view. Dawe Instruments have introduced a variation on previous types in that it measures thicknesses by using a variable frequency oscillator setting up standing waves on reflexion from the further side of the material under examination.

One of the more novel items was the "television microscope" developed by Avimo. This utilizes television circuits to magnify specimens to larger dimensions than is possible with the optical microscope and furthermore enables the demonstration advantages of large screen projection to be used. The specimen is scanned through the optical system of an ordinary microscope by a flying spot scanner and the light transmitted through the specimen is converted by a photo-multiplier to impulses which intensity modulate the viewing cathode ray tube.

Radio Component Show

Over 100 firms exhibited at the Radio Component Show held at Grosvenor House, London, from April 7th to 9th. As in the previous shows considerable evidence was given of successful research by British component manufacturers in the design and production of components. These are increasingly reliable under extremes of atmospheric conditions, technically more efficient and—many of them—smaller in size. Although certain new items are only for Government use, manufacturers are meeting increasing home and export demands.

In opening the show, Sir Robert Renwick, Bart. (Member), stated that the current annual rate of export of components alone was approaching £10,000,000 and if account were taken of the value of components incorporated in equipment, over half the total production of the British component industry was now exported.

Probably the most striking innovations to be seen at the show were in the field of materials. A non-metallic magnet, of ceramic material and having good retentivity, was shown by Mullard, Ltd.; it can be used for focusing units in television receivers. B.I. Callender's Cables, Ltd., have produced a wire insulated by polytetrafluorethylene which can be wound into coils for continuous operation at temperatures from +75°C to +250°C. The insulating film is generally one-thousandth of an inch thick. Multicore Solders have recently introduced a five-core solder which is to be produced in gauges as fine as 22 S.W.G. Advances in magnetic materials for transformer applications were in general mainly seen in new uses of the more efficient steels.

There were a considerable number of firms featuring plugs, sockets and switches which had been specially designed for use in miniaturized equipment. Miniature tuning units, coils and variable and fixed capacitors were also included together with new items recently introduced for television applications. New television tubes included types for wide angle scanning with large, almost flat rectangular faces.

Section Activities..........

LONDON —

When opening a discussion on "V.H.F. and U.H.F. Broadcasting" on April 3rd, Mr. P. Adorian put forward a suggested scheme for future broadcasting in Great Britain. He considered that two channels could, with proper co-ordination of programmes, provide a satisfactory solution to sound broadcasting requirements, while there would also be two television programmes. The majority of home listening would be in the V.H.F. and U.H.F. bands and the long and medium wavebands would serve overseas listeners. He suggested that, because of the more convenient frequency sharing, using a limiter in the receiver to confine reception to the stronger transmitter, frequency modulation was preferable to amplitude modulation. By taking advantage of this "capture" effect, he computed that a third of the number of transmitters would be required in the British Isles when using F.M. than with A.M. Mr. Adorian showed slides of field strength maps illustrating his points, as well as circuit diagrams of various types of V.H.F. receiver. These included a super-regenerative adaptor and four- and five-valve receivers, in which a V.H.F. range had been added to a normal three-band receiver.

Demonstrations were a notable feature of this meeting: Mr. Adorian demonstrated a current German receiver of the type mentioned above which was able to receive the B.B.C. experimental F.M. V.H.F. transmitter at Wortham with quality as good as if not superior to the medium-wave stations. Colonel J. D. Parker (Member) played comparative tape recordings of the reception of medium-wave and V.H.F. F.M. stations in Cologne by day and night and at local and distant strengths. The superiority of the V.H.F. stations under these test conditions was beyond question.

During the discussion which followed, the point was made that it was most desirable for programmes appealing to minorities of listeners to be assured ample broadcast time, and for this reason a multiplicity of stations was favoured. Other speakers wondered whether congestion would ultimately render the V.H.F. region as unsatisfactory as the medium waves were to-day; however, on this point, experience in the German network was reassuring.

The economic problems associated with the adoption of V.H.F. broadcasting received some attention and one speaker suggested that the controversy as to the modulation system employed could best be resolved by continuing the B.B.C. trials on a full-scale basis with both systems for a number of years and then assessing public opinion.

Several speakers deplored the unfortunate effect on exports of radio receivers caused by uncertainty as to the system of V.H.F. broadcasting to be used in this country, and the fact that many countries in Europe and elsewhere had adopted F.M. was put forward as a factor in favour of its firm and early adoption by the B.B.C.

SOUTH MIDLANDS —

One of the most popular of the papers of more general interest which have been presented before local sections during the past session has been Dr. E. G. Richardson's survey of the relationships between acoustic theory and electromagnetic theory. The paper was read to members of the South Midlands Section at two separate centres, Malvern and Rugby, on April 16th and 17th

Dr. Richardson, who is well known as a worker in the acoustics field, showed how the concepts of impedance and the design of filters, transmission lines and waveguides show close analogies between acoustics and radio engineering. Particularly interesting was the interchange between the two sciences—waveguides for instance, were first discussed from the acoustics point of view by Lord Rayleigh, while the study of the propagation of sound waves into the stratosphere has been assisted by the theories marked out for radio wave propagation.

This paper will be published in full in an early issue of the *Journal.*

BOMBAY —

The importance of the study of speech sounds in making the best use of sound reproduction systems for radio, recording and motion pictures was stressed by Dr. M. D. Manohar when he presented a paper before the Bombay Section at St. Xavier's College on February 20th last.

Speech sounds of the English language had been the subject of much research in the U.K. and U.S.A., and Dr. Manohar described preliminary investigations which he had been carrying out on the Aryan languages used in India.

A preliminary survey showed that in connected speech the syllabic power of the Indian language was slightly less than that observed for syllabic power measured by Saccia. It was also observed that the ratio of short average to long average power was larger than that observed by Saccia. This was probably due to the fact that the Aryan languages contained a lesser number of monosyllabic words which again tended to become multi-syllabic due to addition of suffixes in connected speech. Observations on fundamental speech sounds showed that the fundamental frequencies, the energy contents, the duration, and the higher frequency components varied to some extent from similar fundamental speech sounds of the English language. The general observation was that, at conversational level, the speech sounds for the Aryan languages for both male and female voices had slightly higher fundamental frequencies than the corresponding English fundamental speech sounds.

Dr. Manohar suggested that the usual representation of the frequency distribution of fundamental speech sounds by a spectrum graph based on the threshold of audibility curve was not quite correct for speech at normal conversational level. He showed a number of spectrum graphs computed for conversational level which were modified to include the effects of masking and the nonlinearity of the human ear.

DELHI —

The inaugural meeting of the Delhi Section, held on February 3rd, set a high standard in technical papers when Dr. Amarjit Singh (Associate Member) presented a paper on "The Interdigital Magnetron."

The author, who is now in the Physics Department of the University of Delhi, described work he had done at the Electronics Research Laboratory of Harvard University in making an experimental study of the variation of resonance wavelengths of the different modes of an interdigital resonator with variation of its geometrical parameters. The data showed that there was no unique correlation between the wavelength and the length of the "folded transmission line," which had previously been suggested, and it was found that resonance wavelengths could be satisfactorily explained by considering the fingers as loading the cavity instead of as forming a folded transmission line.

Dr. Singh described how, using an operating tube designed to work in the second order mode, oscillations were obtained at the following wavelengths: 4·17, 5·79, 6·04 and 6·15 cm. The cause of the small separation between the last three resonances was studied by observing the field patterns in cold tests and the small separation was finally found to be due to the use of shorting wires for mode control. Four such wires were being used to short-circuit the "folded transmission line" at four places corresponding to the voltage nodes of the $n = 2$ mode. This mode was giving the wavelength 5·79 cm. The shorting wires drastically reduced the wavelengths of the other modes: thus the 4·17 cm mode was the $n = 2$ mode having its voltage nodes displaced by 45 deg with respect to the former mode; the modes at 6·04 and 6·15 cm were $n = 1$ modes, with their voltage nodes displaced by 90 deg with respect to each other.

In view of the above, radial vanes in the cavity were substituted for shorting wires at the fingers, for the purpose of mode control. The length of the vanes lying opposite to each other was the same, but the two pairs had different lengths, and in this way two second order and two first order modes were obtained, at nearly equal intervals of wavelength. Controlled operation at four wavelengths was thus available from a single magnetron.

A method for theoretically evaluating the change in wavelength of a given mode, when a vane is inserted in the cavity, was worked out, the percentage change in wavelength in three test calculations being found to be 15, 7·7 and 4·2 per cent. as against the experimental values of 17, 7·1 and 4·3 per cent. respectively.

It was found that a given resonant mode could be excited at a number of voltages. Dr. Singh attributed this to the fact that in all but the $n = 0$ mode, the interdigital resonator gave a field pattern whose amplitude was not independent of the azimuthal angle. The variation was equivalent to the presence of Fourier components of periodicity different from the periodicity of the fingers. The ratios of the observed voltages agreed with the ratios expected on the basis of the above explanation. The excitation of a mode at extraneous voltages was expected to be reduced if the number of fingers in the cavity was made larger.

DIELECTRIC LOSS OF DIOCTYL PHTHALATE AT ULTRA HIGH FREQUENCIES*

by

S. S. Srivastava, M.Sc., Ph.D., D.I.C. (*Associate Member*)†

SUMMARY

The dielectric loss of dioctyl phthalate in solutions of benzene and liquid paraffin has been measured over the frequency range 10^5 to $2{\cdot}35 \times 10^{10}$ c/s. In benzene the system is characterized by a single relaxation time and the variation of tan δ with frequency conforms to the original Debye theory. In liquid paraffin, the system is characterized by a spectrum of relaxation times. The values of the dipole moment determined from these two sets of measurements agree within 2½ per cent.

1. Introduction

Solutions of polar molecules in simple non-polar solvents exhibit marked dielectric absorption in the decimetric and microwave regions. The magnitude and the frequency of this absorption depend upon the concentration, the dipole moment of the polar group, and the relaxation time which characterizes the orientation of the dipoles in the electric field. These relaxation times are in turn characterized by entropies and energies of activation of dipole orientation and will depend on the size, shape and polarity of the polar group and the properties of the environment in which the orientation is occurring. Experimental technique[1] has now been developed to permit accurate dielectric loss measurements in the decimetric and microwave bands. This technique has been adopted to measure dielectric loss in dioctyl phthalate in benzene and liquid paraffin solutions in the measurements given in this paper.

2. Method of Measurement

Table 1 gives details of the resonant systems used for measurements at various spot frequencies within the range 10^5 to $2{\cdot}35 \times 10^{10}$ c/s.

In the Hartshorn and Ward[2] dielectric test set the measurements were carried out from 10 to 100 Mc/s. The specimen was placed between the plates of a capacitor which formed part of a resonant circuit. Relative permittivity was determined by finding the capacitor plate separation which would produce resonance at the same frequency when air replaced the material under investigation as dielectric. The dielectric loss was calculated from the measured Q-values of the resonant circuit with air and material as dielectric respectively. The circuit Q-value was obtained by variation of the capacitance in the circuit by means of a small capacitor in parallel with the main capacitor. Liquid dielectric was placed in a metal cup clamped to the lower electrode of the variable air capacitor. The whole arrangement was surrounded with a thermostat to regulate the temperature. The presence of the rim in the cup did not affect the observations materially.

In the E_{010} cylindrical resonators the liquid was placed in a thin-walled quartz bottle, the effect of which was taken into account in deriving the expressions for the permittivity and tan δ of the specimen. Transparent quartz has a very low value of tan δ in the microwave region and is therefore best suited for loss measurements. Polythene bottles, however, suffer from the disadvantage that adsorption of many organic liquids distorts the bottle. Mathematical analysis for the three-layer dielectric systems has been worked out by Dunsmuir and Powles[3] and expressions are given for the permittivity and tan δ of the test liquid in terms of the resonant frequency and Q-factor of the cavity with and without the specimen. These expressions reduce to those derived for the two-layer solid dielectric case if the thickness of the bottle wall is reduced to zero.

In the H_{01n} cavity resonator the liquid was placed in a polythene cup formed around a non-contact type of brass piston moving in the cavity between two resonant points. The electro-magnetic field components are not disturbed as the tangential component of the

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electric field is already zero on the wall surfaces. To prevent leakage and swelling of the polythene, a thin paste of celluloid in amyl acetate was painted between the polythene sheet and the metal sides of the piston. Best permittivity values in liquids were obtained by using nearly half specimen wavelength thickness of the liquid in the cavity. With very lossy liquids, however, the amount to be used was limited by the available power in the resonator. The theory of the dielectric loss measurements in H_{01n} cavity has been worked out by Horner, Lamb and Jackson.[1]

3. Solutions in Benzene

Measurements have been made on solutions of dioctyl phthalate in benzene using the above technique. Analar benzene of high purity was used for solution and M/40, M/20 and M/10 solutions of dioctyl phthalate were prepared separately, and the dielectric loss of these solutions together with that of benzene was measured at each frequency. Benzene itself shows a dielectric loss which rises with frequency. The presence of this basic loss has not affected the determination of the additional loss due the polar molecule in benzene. This additional loss is referred to as incremental tan δ and is equal to the total loss measured in solution from which the loss of benzene at that frequency has been subtracted. Measurements with different concentrations showed that tan δ is proportional to the concentration at each frequency. The results are shown in Fig. 1 for dioctyl phthalate solutions in benzene. The temperature at which these measurements were made was well within 20°C ± 1°C.

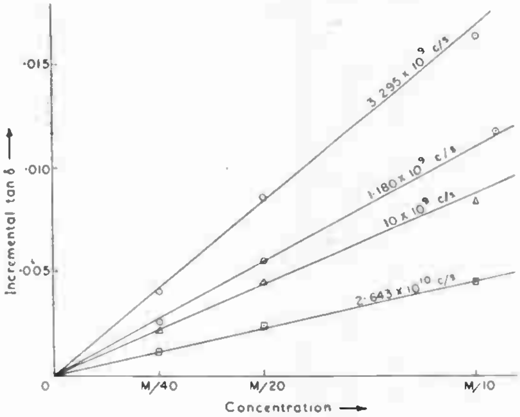

Fig. 1.—Dielectric loss of Dioctyl Phthalate Solution in Benzene (Analar) at 20°C.

Now it is to be expected that the behaviour of these solutions of polar molecules in a non-polar solvent would conform closely to that predicted by the Debye theory.[4] This theory gives the variation of tan δ with frequency, *f*, (in c/s) of dilute solutions of a single type of polar molecule in a simple non-polar medium in the form

$$\tan\delta = \frac{(\Sigma' + 2)^2}{\Sigma'} \cdot \frac{4\pi}{27} \cdot \frac{\mu^2}{kT} \cdot NC \cdot \frac{2\pi f\tau}{1+(2\pi f\tau)^2} \quad (1)$$

In this equation Σ' is the real part of the complex relative permittivity of the solution and for solutions used in the present experiments does not differ significantly from the relative permittivity of the solvent, μ is the dipole moment, and C is the concentration in gm. molecules per cm³ of the polar solute. τ is the relaxation time

Table 1

Frequency of measurement in c/s.	Free Space Wavelength λ in cm.	Resonant system used	Resonator Dimensions	
			Diameter cm.	Length in cm.
10^5 to 10^8	3×10^2 to 3×10^5	Hartshorn & Ward Test set	—	—
$6{\cdot}6\times10^8$	45·5	E_{010}	34·66	15·2
$1{\cdot}29\times10^9$	23·2	E_{010}	17·78	4·73
$3{\cdot}49\times10^9$	8·6	E_{010}	6·58	3·77
$10{\cdot}0\times10^9$	3·002	H_{012} & H_{013}	4·74	4·45 (Variable)
$2{\cdot}35\times10^{10}$	1·275	H_{011} & H_{012} H_{013}	1·906	8·85 (Variable)

of the dipole orientation, k is Boltzmann's constant and N is Avogadro's number.

It is clear from the above equation that tan δ passes through a maximum given by

$$\tan\delta_{max} = \frac{1}{2}\cdot\frac{(\Sigma'+2)^2}{\Sigma'}\cdot\frac{4\pi}{27}\cdot\frac{\mu^2}{kT}\cdot NC\,..(2)$$

$$\text{at the frequency } f_{max} = \frac{1}{2\pi\tau}\;\ldots\ldots\ldots\ldots\ldots(3)$$

Equation (1) can also be written as suggested by Fuoss and Kirkwood[5] in the form

$$\tan\delta_f = A \operatorname{sech} \alpha \log_e \frac{f_m}{f}\;\ldots\ldots\ldots(4)$$

where A is a constant, f_m denotes the frequency at which tan δ_f attains a maximum value and α is a measure of the breadth of the distribution of relaxation times. For a single relaxation time, α is unity and it decreases with increased breadth of the relaxation time spectrum.

A curve, tan $\delta = 0{\cdot}00857$ sech $\log_e (f_m/f)$ is found to be a good fit to the experimental values of tan δ in Fig. 2; $A = 0{\cdot}00857$ is the maximum value of tan δ at a frequency $f = f_m$. The dotted circles in Fig. 2 correspond to the values calculated from this equation. The agreement is sufficiently close to justify the conclusion that only one relaxation time is involved. The acceptance of this curve as a correct representation of the behaviour of solution leads to a value of relaxation time for dioctyl phthalate in benzene of $4{\cdot}8 \times 10^{-11}$ sec at 20° C ± 1°.

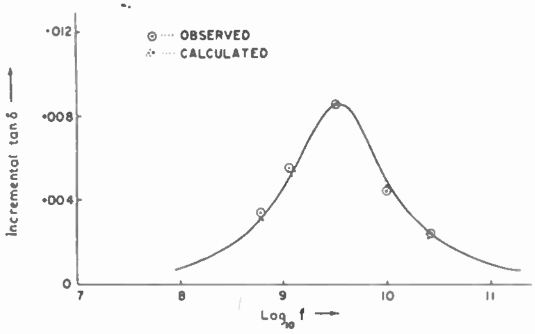

Fig. 2.—Dielectric loss of M/20 solution of Dioctyl Phthalate in Benzene.
Tan $\delta = 0{\cdot}00857$ sech $\log_e (f_m/f)$ *at* 20°C.

Using equation (2), the value of the dipole moment of dioctyl phthalate is $\mu = 2{\cdot}49$ Debye units which is in very close agreement with the values determined by previous workers by thermal and optical methods and also with the value of Richards and Plessner[6] by dielectric loss method in polythene as shown in the Table 2.

4. Solutions in Paraffin

The dielectric loss of dioctyl phthalate was also measured in medicinal liquid paraffin. Proportionality between tan δ and concentration was observed at all frequencies of measurement

Table 2
Determinations of Dipole Moments

Ester	μ in Debye Units	Solvent	Method	Authority
Diethyl Phthalate	2·4	Benzene	Thermal	Estermann
,,	2·7	Benzene	Optical	Williams
,,	2·8	Dioxane	Optical	Williams
,,	2·68	Carbon tetrachloride	Thermal	Bretscher
Dimethyl Phthalate	2·8	Benzene	Optical	Weissberger
Dioctyl Phthalate	2.54	Polythene	Dielectric Loss	Richards & Plessner

and the incremental tan δ values corresponding to M/20 solution were plotted against log f in Fig. 3.

A curve, tan $\delta = 0{\cdot}0072$ sech $0{\cdot}706 \log_e (f_m/f)$ is seen to be a reasonably good fit to the experimental points. The Debye curve is a broad one with a frequency maxima at $6{\cdot}31 \times 10^7$ c/s. and shows a spread of relaxation time around a central τ_{max} of $2{\cdot}52 \times 10^{-9}$ sec.

Following Sillars,[7] it is possible to derive a value of the dipole moment, based on the areas under the tan δ *vs.* log f curve, and since the areas under the curves in benzene and paraffin agree within 5 per cent. it follows that, since the area varies as μ^2, the dipole moment values for dioctyl phthalate afforded by paraffin are in agreement with those of benzene to within 2½ per cent.

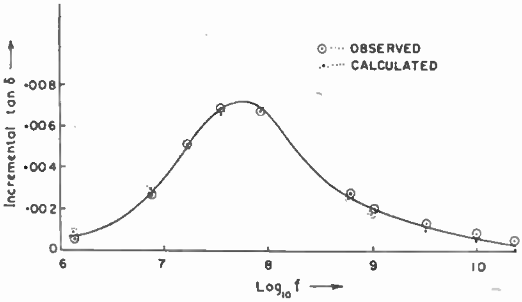

Fig. 3.—Dielectric loss of M/20 solution of Dioctyl Phthalate in Paraffin Oil.
Tan $\delta = 0{\cdot}0072$ sech $0{\cdot}706 \log_e (f_m/f.)$

5. Results and Discussion

From the above measurements it is possible to compare the relaxation times for dioctyl phthalate molecule in benzene and paraffin. According to Debye the relaxation times are related in a manner analogous to the macroscopic viscosities of the solvents. The desired comparison is given in Table 3 based on taking the dominant relaxation time in paraffin as that corresponding to the position of the absorption peak of this solution. It will be seen that the relaxation time and viscosity ratios do not correspond to that required by the Debye theory.

The Debye equations can hold good only under the following conditions:

1. The solution of dipolar molecules in a non-polar medium should be very dilute so that interaction between dipoles can be ignored.
2. The molecules should be axially symmetrical.
3. Only one process leading to equilibrium (e.g. either transition over a potential barrier or frictional rotation) should be involved.
4. All the dipoles on an average should behave in a similar way.

The relaxation time, $\tau = 4\pi\eta a^3/kT$, (where η = viscosity of the medium at temperature T and a is the radius of a solid sphere having the same frictional constant as the dipolar molecule), given by Debye further involves the assumption that the dipolar molecule is fixed fairly rigidly relative to its neighbours so that large jumps of the dipole direction are unlikely. But the temperature dependence of the viscosity

$$\eta \propto e^{H\eta/kT}$$

suggests that jumps over a potential barrier of height H_η are carried out by the molecules of the liquid in processes connected with viscous flow. Therefore, if H is the height of the potential barrier related to jumps of the dipolar molecule, the condition that these jumps happen only very rarely suggests that $H \gg H_\eta$

Table 3

Comparison of Relaxation Time and Macroscopic Viscosity data at 20°C.

Solvent	Viscosity η in Poise	Relaxation Time τ	$\frac{\eta \text{ Paraffin}}{\eta \text{ Benzene}}$	$\frac{\tau \text{ Paraffin}}{\tau \text{ Benzene}}$
Benzene	0·0066	$4{\cdot}8 \times 10^{-11}$	298	51·4
Paraffin	1·97	$2{\cdot}52 \times 10^{-9}$		

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a condition which is more likely to be satisfied by liquids of low viscosity which have small values of H_η than high viscosity liquids.

Richards and Plessner[6] have also studied the dielectric loss of several phthalates in polyisobutylene, polythene and polystyrene. All of them exhibit maxima at radio frequencies. The breadth of the absorption curves shows a spectrum of relaxation times in all the polymers. The dioctyl phthalate molecule shows a single relaxation time in benzene and a spectrum of relaxation times in paraffin; the value of α, which is a measure of the spread, is 0·70, a value very close to that of benzophenone in paraffin measured by Willis Jackson and Powles.[8] This spread seems to be a characteristic of the liquid solvent. The large value of the relaxation time of dioctyl phthalate molecule in benzene is not surprising in view of its large size as the dependence of the relaxation time on the size of the molecule has been recognized by many workers.[9] There is as yet no clear trend to correlate the relaxation times with any physical property of the molecule. It may be possible to understand this behaviour better when more measurements on very large and small solute molecules are available.

6. Acknowledgments

The author gratefully acknowledges the help and guidance given by Professor W. Jackson and Dr. J. Lamb of the Microwave Laboratories of the Imperial College of Science and Technology, where the above investigations were carried out.

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CRYSTAL TRIODES*

by

E. G. James, Ph.D.† and G. M. Wells, B.A.†

A Paper presented before the South Midlands Section on April 11*th*, 1951, *the West Midlands Section on April* 25*th*, 1951, *the London Section on January* 9*th*, 1952, *and the Merseyside Section on February* 7*th*, 1952

SUMMARY

This paper reviews the history of the development and the potentialities of crystal triodes.

The properties of silicon and germanium diodes are described and explained with reference to a simplified picture of the mechanism of conduction in semi-conductors. In particular the importance of accurately controlling very small concentrations of impurities is stressed.

The action of a germanium triode is outlined briefly, and various designs of germanium triode which have been produced are described.

An equivalent network for the germanium triode is given, and the use of this equivalent in designing circuits containing the triode illustrated by a number of examples. It is shown that circuits developed for thermionic valves are generally not suitable for germanium triodes without modification, and also that the germanium triode lends itself to novel circuit developments which would not be feasible with thermionic valves.

The limitations of the germanium triode compared with thermionic valves are considered, and it is concluded that with further development it will probably find many applications in which it performs better than the thermionic valves, but is never likely to compete in certain fields of application.

1. Introduction

The crystal diode, or cat's whisker, as it was then called, was very extensively used as a detector in the earliest days of radio, but with the advent of the thermionic valve it disappeared almost completely.

However, during the early years of the last war it was resurrected for use as a mixer in high frequency radar equipment. The first radar equipments operated at 200 Mc/s, where normal thermionic valves operated reasonably satisfactorily. To obtain better resolution, the frequency was raised to 600 Mc/s (50 cm), and this introduced many difficult valve problems. At this frequency, mixing or frequency changing with multi-electrode valves was almost impossible, and a special small-clearance diode was designed for the purpose, and this operated reasonably satisfactorily.

The next frequency jump was to 3000 Mc/s (10 cm), when the cavity magnetron was developed, and now the performance of the special diode was poor, partly due to lead length, partly to capacitance and partly to electron transit time. It was at this stage that the crystal and cat's whisker came into the picture.

Remembering the early cat's whisker, it appeared possible to make a unit whose dimensions were a small fraction of a wavelength and whose capacitance was low.

A very crude arrangement was first tried and it gave a superior performance to the diode as a 10-cm mixer. Many semi-conducting materials were investigated at that time; these included galena, carborundum, copper pyrites, silicon and germanium. The early measurements indicated that galena and silicon were outstanding, but that galena required a very light contact pressure which made stabilization difficult. Silicon with a tungsten whisker gave about the same sensitivity with a rather higher pressure.

2. The Silicon Rectifier

In view of this result, all the available effort was concentrated on silicon, and to this day, the silicon tungsten combination gives the best operation as a high frequency mixer. It is interesting to note that silicon crystals are now being manufactured for operation at 40,000 Mc/s and higher.

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† Communication from the Staff of the Research Laboratories of The General Electric Company, Limited, Wembley, England.

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The current-voltage characteristic of a silicon-tungsten combination is shown in Fig. 1. The current increases very rapidly when the silicon is made positive with respect to the tungsten, but in the reverse direction the current is small up to about 3 V and then increases rapidly. When used as a mixer, the local oscillator is arranged to apply a voltage swing of about half to 1 V peak about the origin.

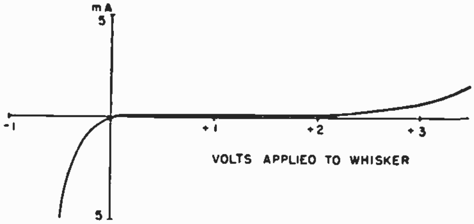

Fig. 1.—Current-voltage characteristic of a silicon rectifier.

3. The Germanium Rectifier

After the war when it became possible to go back to re-examine some of the other semi-conductors, it was found that germanium exhibited some very interesting properties which had been missed in the early days. The most important of these was the very high voltage which it could withstand in the reverse direction.

A typical current-voltage characteristic of a germanium crystal with a tungsten whisker is shown in Fig. 2. The direction of easy flow is opposite to that of silicon, and the voltage in the reverse direction can be increased to about 150 V or more before breakdown occurs. This is about 50 times that obtained with silicon.

This high voltage phenomenon with germanium was missed in the early experiments because the germanium available was not very pure. In fact, it is only possible to obtain a high reverse voltage with very pure germanium.

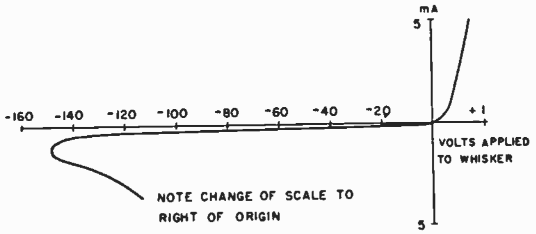

Fig. 2.—Current-voltage characteristic of a germanium rectifier.

4. Conduction in Silicon and Germanium

The reason for the reversed polarity is to be found in the structure of the crystal lattice of the elements.

The atoms of both silicon and germanium have four electrons in their outer ring and their crystal structure is identical with that of diamond.

A crystal of pure silicon or germanium has very low electrical conductivity. This is because all the outermost electrons of the individual atoms are occupied in forming bonds to neighbouring atoms, and they become very tightly bound. However, if a small number of atoms having either three or five outer electrons are introduced into the crystal lattice, then the electron behaviour is entirely changed.

For example, if in a germanium crystal lattice one of the germanium atoms is replaced by an atom of antimony which has five outer electrons, four of these electrons will form bonds with four adjacent germanium atoms, while the fifth will tend to orbit about the antimony atom. It will, however, be loosely bound and will easily move under the influence of an electric field. This type of semi-conductor in which the current is carried by electrons is known as an *n* type semi-conductor—the "*n*" standing for negative electrons.

On the other hand, if an impurity atom such as boron which has three outer electrons, is substituted for a germanium atom, there will be an electron missing from the lattice. Conduction will now take place because electrons tend to jump into the vacant position or hole leaving another hole to be filled, and so on. This type of semi-conductor is known as a *p* type semi-conductor, because the vacant positions or holes behave as positive charges, and are called positive holes.

Silicon is usually a *p* type semi-conductor, whereas germanium is usually *n* type.

When a metal is brought into contact with a semi-conductor, a potential barrier is set up, the direction of which depends on the relative energies of the electrons in the metal and semi-conductor. With *n* type germanium and a tungsten whisker, the energy of the electrons in the germanium is higher than that in the tungsten, and some will spill over into the metal, leaving behind them impurity centres which have a net positive charge. A field is thus set

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up which will grow until equilibrium is reached.

If an external potential is now applied, the field or potential step at the barrier will act as a valve which allows current to flow very much more easily in one direction than the other.

The peak reverse or turnover voltage of a germanium rectifier appears to be related to the width of the potential barrier, and this, in turn, is dependent on the amount of impurity in the germanium. The lower the impurity content the higher the turnover voltage, and this is borne out by the following table which shows the dependence of turnover voltage upon arsenic content.

Arsenic Content parts per million	*Turnover Voltage*
5	24
4	26
3	28
2	33
1	48
0·5	69
0·2	90

It is seen that the arsenic content must be less than two parts in 10^7 if we are to obtain a turnover voltage of 100 V. (It is interesting to note that food is considered safe for human consumption if the arsenic content is less than five parts per million.)

5. Germanium Triode Design

In 1948, Bardeen and Brattain, of the Bell Telephone Laboratories, announced their discovery that if two metal points are placed in close proximity—about 0·005 in. apart—on the surface of a germanium wafer and d.c. potentials are applied to both, then there is a mutual interaction between them which makes it possible to amplify d.c. voltages.[1]

Each electrode operated independently has a current voltage characteristic identical with that of the high back voltage rectifier. If, however, a negative voltage is applied to one of the electrodes, usually called the "collector," then the current to it can be varied by varying the positive voltage on the other, called the emitter. This property gives the device the ability to act as a triode valve.

Figure 3 shows a family of collector voltage-collector current characteristics of a typical triode for various emitter voltages.

The explanation of the operation of the triode is still the object of much argument, but it appears that both electrons and holes play a part in the operation. The theory generally accepted is that when the emitter electrode is made positive, electrons flow from the germanium to it, and, simultaneously, positive holes flow from the emitter to the germanium. The collector being negatively biased, attracts these positive holes, and so the collector current increases.

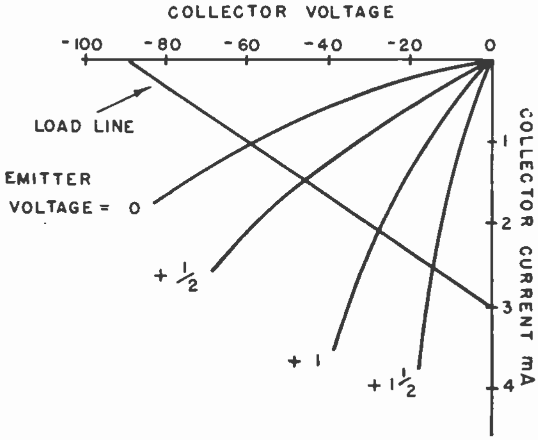

Fig. 3.—Collector current/collector voltage characteristics of a germanium triode for various emitter voltages.

Now, in many triodes, the increase of collector current is greater than the increase of emitter current, i.e. there is a current gain. This is thought to be due to the fact that the potential barrier at the collector electrode is reduced by the concentration of positive holes in its immediate vicinity, thereby causing an increase of reverse current.

The one experimental fact that all are agreed on, is that it is necessary to have very pure germanium, i.e. germanium capable of making very high back voltage rectifiers to make triodes which have reasonable control action.

Two forms of triode assembly have been described by the Bell Telephone Laboratories. In the first (Fig. 4) a small block of germanium is soldered to a metal disc which is supported and makes good electrical contact with a metal cylinder. The two whiskers are formed from thin tungsten or phosphor-bronze wires, about 0·003 in. in diameter. These are supported by

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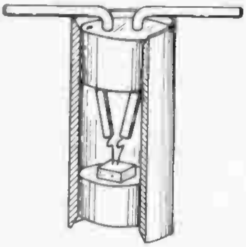

Fig. 4.—
B.T.L. transistor type A.

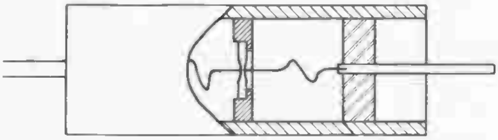

Fig. 5.—B.T.L. transistor type B.

two rods which also act as lead wires. The whiskers make contact with the upper face of the germanium about 0·002 in. to 0·003 in. apart.

In the second Bell Telephone Laboratories design (Fig. 5), a small disc of germanium about $\frac{1}{8}$ in. diameter is cut from a slab of germanium and dish-shaped depressions are ground and lapped into the two faces. The disc is then supported centrally in a metal tube and two whiskers are arranged to make contact on to the germanium in the two depressions.

Whichever of these designs is used, the most critical and delicate operation during manufacture is the adjustment of the two whiskers to their optimum position relative to one another. An attempt has, therefore, been made to evolve a design which would need less skill during assembly. One such design is shown in Fig. 6.

The whiskers in this case consist of two phosphor-bronze blades, 0·003 in. thick and 0·04 in. wide which are supported in a moulded insulator. In order to attain a controlled gap between the blades, one method of manufacture which has been used successfully is to mount a single strip across the channel in the moulding and subsequently shear a gap 0·003 in. wide with a specially designed cutter. Another method is to make two separate blades and adjust them to the correct spacing with the aid of an optical viewer. Both methods give an extremely close control of the whisker spacing.

The germanium is soldered on to the end of a metal stub, and is ground to a cone. By inserting the apex of the cone into the gap between the metal blades (Fig. 7), two-point contacts on to germanium are obtained, with an accurately controlled spacing. Two flexible wires form the external connections to the emitter and collector, and another wire, soldered to the stub supporting the germanium, forms the connection to the base. The unit can therefore be soldered directly in the circuit without the use of a socket.

6. Crystal Triode Applications

One way to use the germanium triode as an amplifier is to earth the base electrode, apply the input signal to the emitter and take the output from the collector as shown in Fig. 8.

The large signal performance of this circuit can be predicted from a set of static characteristics such as that shown in Fig. 3. As with a normal triode, the voltage gain and power output can be obtained if a load line corresponding to a resistor R is superimposed on the characteristics. In order to obtain the input resistance and the driving power, we must also, of course, have a similar set of emitter current-emitter voltage characteristics, just as we would with a normal triode which was being driven into grid current. It is interesting to note here that when the emitter is made more positive, the collector voltage becomes less negative, i.e. more positive. That is, there is no phase change as with a normal thermionic triode.

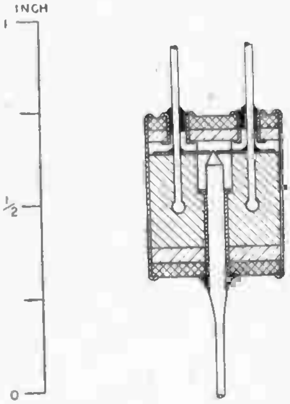

Fig. 6.—
G.E.C. germanium triode.

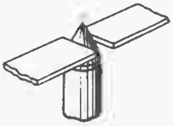

Fig. 7.—
Whisker details of G.E.C. triode.

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When dealing with small signals, it is useful and instructive to be able to deal with the triode in terms of some equivalent circuit.

If we treat the triode as a box with two input and two output terminals, there are a number of possible equivalent circuits which we can put in the box.

One of the most useful equivalent circuits is that shown in Fig. 9.[2] There are three resistances; r_e associated with the emitter contact, r_c with the collector contact and r_b with the base contact. The active property of the triode is described by the inclusion of a voltage generator $r_m\, i_1$, where i_1 is the a.c. component of the input current. The external bias voltages and currents are not shown. Typical values are:—

$r_e = 250\Omega$, $r_c = 20{,}000\Omega$, $r_b = 300\Omega$, $r_m = 35{,}000\Omega$

The input impedance, output impedance and gain can be calculated from this circuit in the usual manner. If one carries out the analysis, one finds that the input impedance is of the form

$$R_i = r_e + r_b - \frac{r_b\,(r_b + r_m)}{R_L + r_c + r_b}$$

Now if an external resistance is connected in series with the base electrode, r_b is increased and it is possible to make the negative term greater than the positive term. When this occurs the circuit becomes unstable.

Another way to look at this phenomenon is to examine the currents in the two meshes of the network.

The net current through r_b is $i_b = i_2 - i_1$.

If $i_2 = \alpha i_1$

Then $i_b = i_1\,(\alpha - 1)$ and the voltage drop across r_b is $= r_b i_1\,(\alpha - 1)$.

If α is greater than 1, then it is possible to make this voltage equal to V_g. That is, the current is self maintained.

If therefore a tuned circuit of a sufficiently high dynamic resistance is inserted in series with the base, the triode will oscillate at approximately the resonant frequency of the tuned circuit.

The earthed base circuit is similar in many respects to the earthed or grounded grid thermionic triode circuit. For example, both have low input impedance, high output impedance and no phase change between input and output The big difference between them is the current gain which one can get with the crystal triode, whereas there is no current gain in the case of the grounded grid thermionic triode.

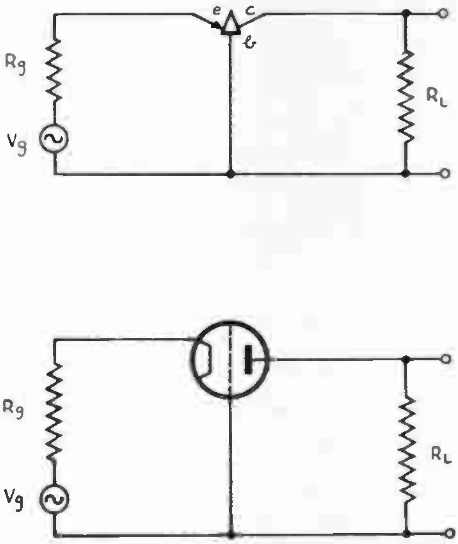

Fig. 8.—Grounded base amplifier.

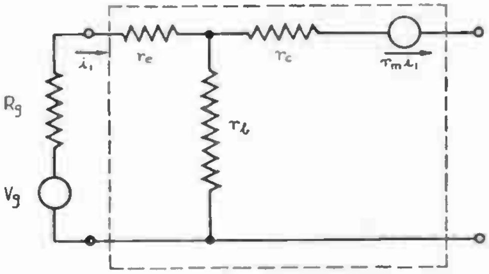

Fig. 9.—Equivalent circuit of germanium triode.

Since, in the above example the emitter was found to be analogous to the cathode, the base to the grid, and the collector to the anode of a normal triode, it is reasonable to assume that an earthed emitter circuit (Fig. 10) behaves similarly to the earthed cathode triode circuit. The behaviour is very similar when α is slightly less than unity, in that the input and output impedances are fairly high. But when α is greater than 1, then the circuit is difficult to handle owing to the fact that we now have an appreciable resistance in the base lead which tends to make the circuit unstable. However, one can cure this by adding resistance in the collector circuit so as to make the effective value of α less than unity.

The power gain of this circuit is usually greater than that of the emitter input circuit. A typical value is 25 db, but higher values can be obtained. The power output is very similar to the first circuit.

The third way to use a triode valve is as a cathode follower. In the germanium triode analogue, the collector is earthed and the output is taken from the emitter (Fig. 11).

Again when $\alpha = 1$, this circuit behaves very much like the usual cathode follower circuit, in that the input impedance is fairly high and the output impedance low.

However, when α is greater than unity, the circuit loses its resemblance to the cathode follower and begins to transmit in both directions; that is, it has gain in both directions.

When $\alpha = 2$, the gain in both directions is the same, and for α greater than 2, the backward gain becomes greater than the forward gain. A curious feature of this circuit is that the forward transmission has no phase change, whereas the reverse transmission has a phase change of 180 deg.

This type of amplifier opens up some interesting possibilities in the field of line communications, in that it is possible to carry a two-way communication with only two wires instead of three as at present.

Amplifiers can, of course, be cascaded to obtain greater overall gain. The emitter input amplifier will, however, need insterstage transformer coupling in order to match the high impedance to the low input impedance.

It is easier to design a multi-stage amplifier using the base input circuit, since in this case no matching transformers are necessary. The thing to be careful about is that when α is greater than 1, oscillation may occur if the resistance in the collector circuit is not high enough.

We have made a three-stage amplifier of this form which was stable, and in which the overall gain was 66 db.

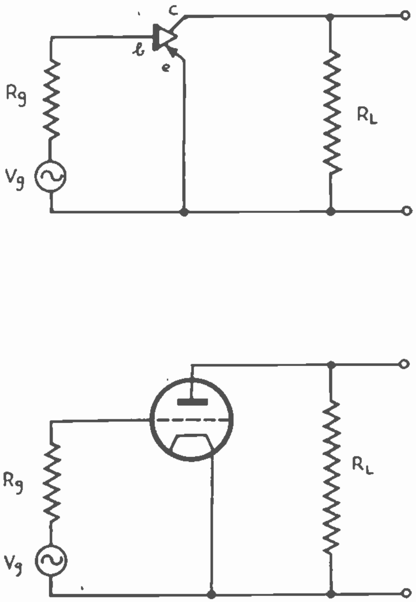

Fig. 10.—*Grounded collector amplifier.*

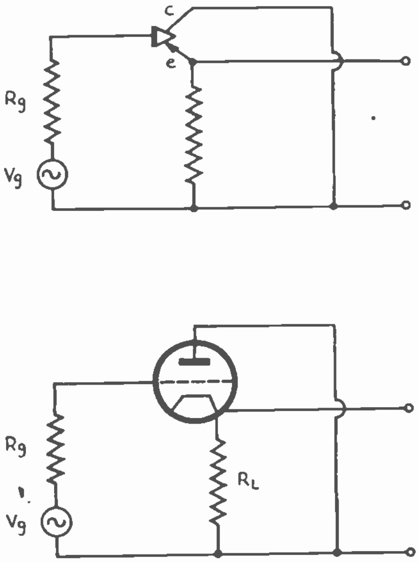

Fig. 11.—*Grounded emitter amplifier.*

Since the characteristics of the triode have curved portions, it is possible to use the triode as an anode (or collector) bend detector. Fig. 12 is the circuit diagram of a complete radio receiver which has operated satisfactorily. It incorporates four emitter input R.F. stages, and an "anode bend" detector driving a push-pull output stage giving about 50 mW output.

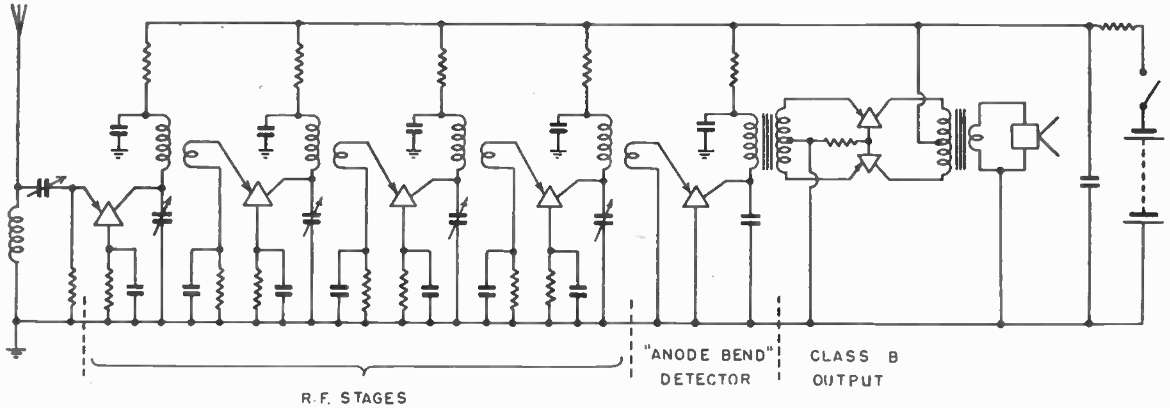

Fig. 12.—Germanium triode radio receiver.

One type of oscillator circuit which can be used with the germanium triode has already been mentioned. Another obvious oscillator circuit is that in which the tuned circuit is in the collector circuit and a feed-back coil is connected in the emitter circuit.

A field where the crystal triode is likely to prove very useful is the computor field where counting is usually performed with pairs of triodes operating in an Eccles-Jordan or a "flip-flop" circuit. This arrangement has two stable states and a pulse is arranged to trip the pair from one stable state to the other.[3]

It is possible to arrange two crystal triodes in a similar "flip-flop" circuit, and reap the very large saving in heater current. The cathode heating of the valves in a modern electrical computor is very embarrassing as not only does the equipment get hot, but so does the room itself, and cooling becomes a major difficulty. The transistor should go a long way to solving this difficulty.

The unstable feature associated with a crystal triode having a resistance in the base lead makes it possible to design one triode circuit with two stable states, so that with this arrangement the number of counting valves is halved. For these reasons, computing is likely to be one of the first fields to adopt crystal triodes in preference to thermionic triodes.

7. Peculiarities of Crystal Triode Circuits

The above examples give an idea of the possible applications of the crystal triode in terms of analogies with the thermionic triode. It will have been noticed that the analogies are by no means complete. This is hardly surprising since the control actions in the two types of valve are radically different. In one case collector current is controlled by emitter current, in the other case anode current is controlled by grid voltage.

It has recently been pointed out by Wallace and Raisbeck[4] of the Bell Telephone Laboratories that the crystal triode is analogous to the vacuum triode if every voltage applied to the vacuum tube is compared with the corresponding current drawn by the crystal triode and vice-versa. That is, the crystal triode may be regarded as the "dual network" of the thermionic triode. This conception provides a most useful approach to circuit design. We will give two specific examples to illustrate the need to devise special circuits for crystal triodes.

The low input impedance of the grounded base amplifier has been mentioned. For an ideal crystal triode this would be zero ($r_e = r_b = 0$), making the input power zero and the power gain infinity. A practical consequence is that it is often better to connect the emitter circuit of the triode in series with a tuned circuit rather than in parallel with it.

The instability of the grounded emitter amplifier when α is greater than 1 may be expressed in terms of negative values of input and output resistance. As the threshold of instability is passed due to an increase of α, the output resistance drops to zero and then assumes larger and larger negative values, whereas the input resistance rises to infinity and then falls from very high to low negative values. This implies that a suitable series-tuned circuit connected to the

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output will oscillate at its resonant frequency, while a parallel tuned circuit will oscillate on the input side.[5] Coupling filters for a cascade of such amplifiers should be designed so that outside the pass band they present high impedance to the output circuit and low impedance to the input circuit. If this is not done, oscillation at some frequency outside the pass band will probably occur.[6]

8. Limitations and Scope of Crystal Triodes

A semi-conductor, such as germanium, allows current to flow at normal temperatures because electrons become detached from some of the impurity atoms in the lattice and jump to neighbouring impurity atoms which have lost an electron. Since this movement of electrons takes appreciable time, the change in the collector current resulting from a change of emitter current only occurs after a finite time delay. This means that the collector current lags behind the emitter current. This effect limits the maximum frequency of operation of existing triodes to about 10 Mc/s.

As one would expect the maximum frequency is dependent on the spacing between the whiskers, but there are also other factors which have not yet been sorted out.

As is well known, the Shott noise generated in a thermionic valve is constant at frequencies above a few kilocycles, but below this frequency the noise increases. This low frequency noise is known as flicker effect and is inversely proportional to frequency.

The same sort of thing happens with crystal triodes, but with the difference that the low frequency noise extends to a much higher frequency—of the order of a few megacycles—and is greater in magnitude than that of thermionic valves. The exact mechanism of the noise generation is not at all clear at the moment, but is probably connected with the migration of ions over the contact between the metal and the crystal.

If we express the noise as an equivalent voltage at the input of the triode—assuming an emitter input circuit—and taking a bandwidth of 4 kc/s, then this equivalent voltage is about 5 μV at 1 Mc/s, 25 μV at 100 kc/s, and 70 μV at 10 kc/s. This means that one cannot use a crystal triode as the first stage of a high gain audio amplifier.

However, at the order of 1 Mc/s the magnitude of the noise is reasonable, and is not noticeable in a receiver designed to amplify a signal of the order of 1 mV. This is typical of a local station receiver.

It is inevitable that there should be much speculation as to how far the crystal triode will replace thermionic valves. There is no doubt that the crystal triode has a number of advantages over the thermionic triode, but it also has a number of disadvantages.

Among the advantages are: the absence of a heater simplifies many circuits and, since no "warming-up" time is required, the equipment would operate instantaneously; the life should be very long since it has no sensitive cathode; while the triode can be made very rugged, so that microphony is not likely to be troublesome.

The disadvantages at present are: the power output is limited; the maximum frequency of operation is limited to about 5 to 10 Mc/s, and the device is inherently more noisy than a thermionic valve.

One can fairly safely predict, therefore, that the crystal triode, when it has been further developed, will find many applications where it will perform better than the thermionic triode, but there are others where it is never likely to compete. One will find, therefore, that one is likely to be complementary to the other.

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LONDON SECTION DISCUSSION

Dr. A. L. Allen: Can Dr. James explain why such emphasis is placed on arsenic as the impurity in germanium, but comparatively little on others such as boron and antimony? Are the elements simply not present in the original crude germanium, or is it that they are more volatile or more easily removable by chemical treatment than arsenic? The fact that tin is admissible—and sometimes deliberately introduced—in quantities up to 0·1 per cent. makes me suspect that Dr. James may have a deeper physical explanation to offer and that arsenic may supply electrons much nearer in energy level to the "conduction band" than any other element would, and is therefore admissible in much smaller quantities.

Secondly, has Dr. James an explanation of why, in point contact rectifiers, the contact area has to be so small, yet in *n-p* junction type rectifiers this is not necessary? Would he be prepared to go so far as to say that our crystals are such a mixture of unknown impurity centres that the whisker point has to be small to ensure that it stands on an *n* type centre only, and does not spread over both an *n* type and a *p* type impurity centre, while the base contact conducts both ways because it covers both *n* type and *p* type areas? Has the steep potential gradient at the point contact nothing to do with the rectifying action?

K. A. MacKenzie (*Associate Member*): Dr. James mentioned that humidity has a detrimental effect on the contact transistor which therefore is hermetically sealed into its can. I would like to know if the units are evacuated before sealing and whether the same precautions are necessary with the junction type transistor?

Secondly, could Dr. James give us some idea of the effect of temperature on the characteristics of junction transistors?

L. R. Hulls: If an electric charge is induced on the surface of a semi-conductor, such as germanium, a proportion of the electrons composing the charge are available for increasing the conductivity of the semi-conductor. In view of the fact that, from a circuit point of view, the transistor in a number of cases suffers from the disadvantage of having a comparatively low input impedance, I should be most interested to learn if the phenomenon outlined above could be used as the basis of a high input impedance crystal valve?

L. F. Oliver (*Associate*): I presume that the only difference between the emitter and collector electrodes is in the voltages applied to them, and therefore there seems no theoretical limit to the number of cat's-whiskers that can be connected to any one crystal. With grounded base and two emitters the effect of a double triode with strapped anodes would thus be obtained, which could be used as a mixer for two inputs. Alternatively a combination of multiple input and rectification might give frequency mixing as in a superheterodyne receiver or possibly an analogue of the "nonode" recently introduced for f.m. detection. Have these possibilities been considered ?

F. F. Roberts: The authors make no mention of the electrical "forming" process which distinguishes the new from the old-fashioned cat's-whisker crystal contacts. Is it now considered that this "forming" results in the production of a *p-n* junction in the germanium below the metal contact, and that the contact itself is not the primary source either of the rectification or of the hole emission (in *n* type germanium) effects? To what extent is it thought that the phosphorus in a phosphor-bronze cat's-whisker assists in the production of such a junction?

The explanation of the inherent frequency limitation given in the paper is surely incomplete. Any single finite time delay applying equally to all frequencies would have no effect on the gain/frequency characteristic.

Extremely wide variations have been found for the gain, frequency response and noise characteristics of the earlier transistors produced both in the U.S.A. and in this country. I am sure the many potential users look forward to the day when these devices will be available in quantity to close tolerances and in reliable form.

F. P. Thomson (*Associate Member*) (*communicated*): What is the supply position with respect to germanium and how does its "finished state" cost compare with, say, silicon crystal for microwave rectification? Secondly, is there any ground for believing that the choice of the crystal axis (or facet) on which the cat's-whisker rests is a sensitivity determinant? The authors mention that a certain amount of heat generated at the point of rectification aids sensitivity. Does the heat generated ever exceed A.I.D. Tropical Test maximum

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temperatures before there is an impairment of the crystal's efficiency, and has thermal lagging of the crystal capsule been attempted with a view to smoothing out sudden temperature changes and sensitivity conditions which might occur when the triode is used, for example, on airborne equipment?

AUTHORS' REPLY TO DISCUSSION

Arsenic appears to be the main residual impurity in germanium which has been refined to a purity suitable for high back voltage rectifiers. This is due to the great difficulty of removing the last traces of arsenic. We are dealing with such extremely small amounts of impurity that it is not possible to say with absolute certainty that no other elements than arsenic are playing a part. Both boron and antimony have been used as deliberate additions to germanium to achieve particular results (in the case of boron the germanium becomes *p* type). Tin has the same valency as germanium and, therefore, neither contributes excess electrons nor positive holes.

In both the point contact and the junction type rectifier it is necessary to make connections at which the potential drop is small enough to have little effect on the rectifier characteristic. While in the point contact case it is possible to achieve this simply by reason of the large area of the case contact, it is preferable to make a truly "ohmic" connection by using a metal such as tin or lead which alloys with the germanium. In the case of the junction rectifier this is essential because the area of the junction is of the same order as that of the end connections.

The germanium used for rectifiers is *n* type over its entire area, so that there is little possibility of a relatively large area-contact not rectifying because of cancellation of *p* and *n* zones.

The explanation of the formation of a potential barrier at a *p-n* junction has been dealt with very fully in the literature* and cannot be adequately dealt with in a short reply.

A type of semi-conductor amplifier has been described† which appears to operate by a mechanism of the kind suggested by Mr. L. R. Hulls.

A three-whisker germanium device has been suggested and this can be used with two emitters and one collector as a frequency mixer, as suggested by Mr. L. F. Oliver.

The mechanism of electro-forming is far from being fully understood. It has, however, been suggested that a "*p-n* hook" is formed in the vicinity of the collector during the forming process. This could be caused by the formation of lattice defects or by the introduction of *p* type impurities from the whisker.

As Mr. Roberts points out, the fall-off in triode performance at high frequency is due to the spread in the transit time of the holes flowing from emitter to collector.

The supply of germanium in this country is likely to be adequate for all our needs for many years, and the cost of purification is very similar to that of silicon used for microwave crystals.

We know no evidence to indicate that the choice of crystal orientation relative to the whisker affects the sensitivity.

As the temperature is increased the collector resistance decreases, but we have as yet insufficient evidence to indicate whether triodes will operate successfully at the high temperature called for in some services equipment.

It is not necessary to evacuate germanium assemblies, as long as precautions are taken to seal dry air into the units.

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*For example, W. Shockley, *Bell Syst. Tech. J.*, 28, July 1949, p. 435.

†O. M. Steutzer, *Proc. I.R.E.*, 38, Aug. 1950, p. 868.

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JOURNAL OF THE BRITISH INSTITUTION OF RADIO ENGINEERS

THE FOCUSING OF CATHODE RAY TUBES FOR TELEVISION RECEIVERS*

by

J. A. Hutton, B.Sc.†

A Paper presented at the Fifth Session of the 1951 *Radio Convention on August* 23*rd in the Cavendish Laboratory, Cambridge*

SUMMARY

The object of the paper is to summarize the various effects which control the focus of a television picture from the point of view of a receiver designer. (Any effects connected with tube design are neglected.)

The cause of deflection defocusing and the resultant aberrations are discussed and remedies set out.

The divergence of the focusing field from a convex lens and the effects of the position of the field on focus control are detailed. The effect of supply potential variation on E.H.T. and focus field are dealt with and finally E.H.T. supply regulation is considered.

1. Introduction

The following paper consists of a summary of the known causes of defocusing over which the designer of a television receiver has control.

Magnetic cathode ray tubes only are considered, and it should be noted that, as a rule, triode tubes are inferior to tetrode tubes from the point of view of defocusing effects. This is due to the fact that under similar conditions the beam width and focusing field intensity are both greater in the case of triodes.

The advent of tubes with scanning angles increased beyond those to which we are accustomed accentuates many of the effects described and may cause results which are intolerable unless the components and methods which have been used successfully in the past are suitably modified.

The order in which the various effects are treated is not that of importance. Perhaps the most common causes of poor focus are inadequate E.H.T. potential and inadequate E.H.T. regulation. Nevertheless, it is felt that more attention could profitably be paid to the other effects discussed, for frequently the definition in the corner of a picture is limited by the focus rather than the bandwidth of the R.F., I.F., and video amplifiers of the receiver.

There are many effects which are not considered, which fall into the category of Cathode Ray Tube design.

2. Deflection Defocusing

One of the most serious causes of picture defocusing is attributable to the shape of the scanning fields. This effect, deflection defocusing, manifests itself as bad focus in the corners of the raster.

It is widely believed that, given a spherical tube face, the centre of curvature of which is in the scanning field, and using a linear field (the condition associated with a cosine law of ampere—turn distribution) no defocusing would occur. This is not the case, however, as is indicated by Fig. 1 in which the deflecting field is assumed to be constant over the shaded portion and directed out of the paper.

If the speed of the axial electrons is V_1 and of the convergent electrons $V_2 = V_1/\cos\gamma$, where γ is the angle of convergence, the radius of curvature of the axial ray is

$$r_1 = \frac{mV_1}{He}$$

and of the convergent ray

$$r_2 = \frac{mV_2}{He} = \frac{r_1}{\cos\gamma}$$

The locus of intersection of rays under these conditions presents a laborious mathematical problem, and has been found graphically in the diagram. The exact result is not of paramount importance since, as indicated by the diagram, a linear field would never be used in practice, even if it could be produced. Clearly the type of field required is one which diminishes as the distance from the axis is increased, so that the outside rays are deflected less than the axial ray.

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† Murphy Radio, Ltd.

U.D.C. No. 621.397.331.2.

The required field shape cannot be expressed usefully in words or figures, and the designer of scanning coils must inevitably check his design by inspecting the quality of focus on the raster. It is useful, however, to have some means of examining the actual field shape to ensure that there are no asymmetries or irregularities. A satisfactory device for this purpose has been found to be a cell which corresponds to the size of a C.R.T. neck in which steel filings float on the surface of mercury and indicate lines of force when subject to the magnetic field derived from combined alternating and direct current in the scanning coils. The most successful unit is illustrated in Fig. 2. Gentle agitation of the unit causes the steel particles to rise in the oil before the field is applied. They then settle slowly on to the surface of the mercury forming patterns which can yield much information, the required departure from field linearity being easily discernable.

As will be shown, under no practical conditions can a deflected beam be free from some measure of deflection defocusing, but we can determine the conditions for minimizing the effect.

One condition for reduction in defocusing is that the focal surfaces of deflection in both the line and frame directions should be coincident. Since each of the focal surfaces will be the surface of revolution, centred on the scanning field, of some line, it is clear that the surface of revolution must be a sphere, and the focal lines must be circles with the scanning field as centre.

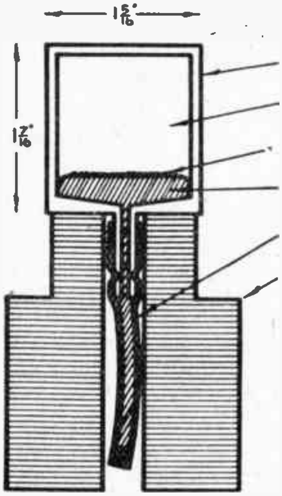

Fig. 2.—A device for examining the shape of a deflection field.

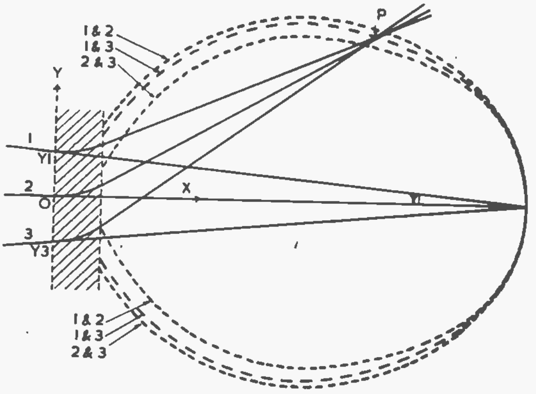

Fig. 1.—The focal lines of electron rays deflected by a linear field.

This condition implies that we have a field which is diminishing in the direction of y as $|y|$ increases, but is constant in the directions of x and z within the volume of the scanning field. This condition is impossible since div $H = 0$, and if we arrange for the field to vary such that $dH/dy \neq 0$, then $dH/dz \neq 0$, and we shall have a family of lines of force which are either "pin-cushion" or "barrel" shaped.

The fact that dH/dz is not zero will cause astigmatism, the meridional and sagittal planes being widely separate when the deflected angle is not small. It will also have an effect upon the geometry of the picture.

Another condition is that all the rays in any one plane should meet in a point. Referring back to Fig. 1, this means that the axial ray, ray 2, must be so deflected as to meet rays 1 and 3 at P, since, if the field is symmetrical, no change in dH/dy will affect the locus of P, as H at a distance ($L \tan \gamma$) from the axis will be the same as at a distance ($L \tan (-\gamma)$). If this condition is not held, a form of spherical aberration is clearly present, but unfortunately, the locus of intersection of rays 1 and 3 is not a circle centred on the scanning field as required by the previous condition. It would be possible to alter the locus of intersection of rays 1 and 3 by having an asymmetric field, the asymmetry being dependent upon the phase; thus, if the beam were being deflected in the direction $+y$, the field at $+y_1$ which affects ray 1 would be greater than the field at $y_3/[= -y_1]$ which affects

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ray 3, and would be increasingly greater as the deflected angle was increased. Conversely, if the beam were being deflected in the direction $-y$, the field at y_3 would be greater than that at y_1. This field non-linearity would be difficult to produce, probably requiring two non-linear amplifiers, and the resulting benefits could hardly be considered to justify the effort.

We are therefore faced with having either spherical aberration on an "elliptical" surface or astigmatism on a spherical surface.

A third condition is that the length of the scanning field in the x direction should be short, so that the change in distance of an electron from the axis within the scanning field is small, and the consequent change in the value of H negligible. This condition conflicts with electrical conditions, for the electrical efficiency of a scanning coil is proportional to its length.

To add to the difficulties, the surface upon which the image is to be obtained, the tube face, must have a very small curvature for satisfactory viewing, so that even if it were possible to produce an image without aberration on either of the two focal planes considered, the result would be poor on the face of the tube.

There is, however, one further method of attacking the problem, namely, the alteration of the focal length of the focusing lens in accordance with the deflecting field. This is a promising idea which has the electrical disadvantage of requiring a decrease of focusing field flux with increased deflection angle irrespective of the sign of the deflection. In general, both spherical aberration and astigmatism will be present, but considerable improvement in overall focus can be obtained. From the point of view of aberrations, the effect of such a system is to alter the relation of the curvature of the tube face to the curvature of the focal surfaces.

It would appear from the preceding arguments that no magnetically deflected picture can be free from aberrations, and one might expect results to be very much worse than are obtained in practice, unless elaborate precautions are taken. In looking at Fig. 1 one should remember that in practice γ is very small (the order of 1 deg.) and the resultant defocusing effects can be made quite small with proper design. This has not prevented television receivers being marketed in this country and abroad which have badly designed scanning coils and consequently poor corner focus.

As will be discussed later, deflection defocusing is affected by the position of the focusing field, movement of which varies the beam width in the scanning field, and also by the magnitude of the E.H.T. potential. Increase of the E.H.T. potential has the dual effect of reducing the beam width and thus reducing the deflection defocusing, and also reducing the size of the spot on the screen so that a greater amount of defocusing can be tolerated.

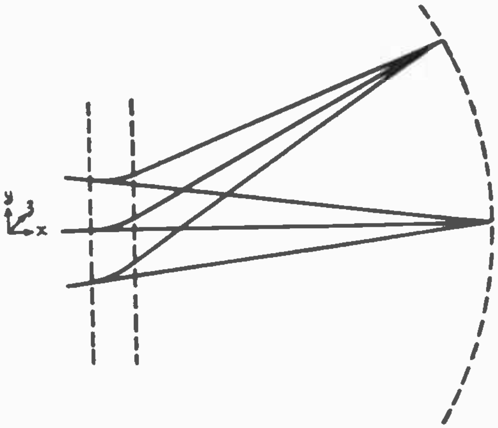

Fig. 3.—The focal line due to a desirable scanning field.

In examining deflection defocusing, it is necessary to exercise considerable care. The first condition is that the beam should pass through the centre of the scanning field. This may or may not be the same condition as having the raster central on the tube face. The second condition is that the beam current magnitude is taken into account, for it sometimes happens that the raster appears to be quite well focused with very small beam currents, even though serious deflection defocusing is present. Thirdly, as follows from the preceding paragraph, in comparing two scanning units, the same tube, E.H.T. potential, focus field position and shape must be used.

The criterion for good corner focus is that the spot size should not be appreciably greater than in the centre of the picture, and that the spot shape should be reasonably circular. The common method of examining these phenomena is by observing the apparent thickness of the scanning line, but this clearly does not reveal

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any defocusing in the line direction. It is quite possible to obtain a spot which is elliptical with the major axis in the line direction—the condition associated with a linear line field and corrected frame field. The effect of this is to reduce the definition in the line direction rather than in the frame direction and hence the line thickness indicates far less defocusing than is actually present.

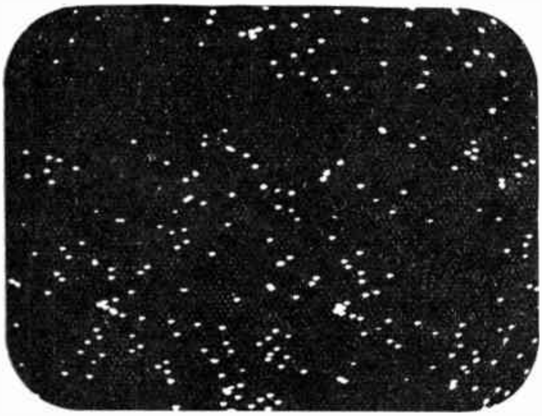


Fig. 4.—Examination of spot shape in different parts of a raster by the spark gap method.

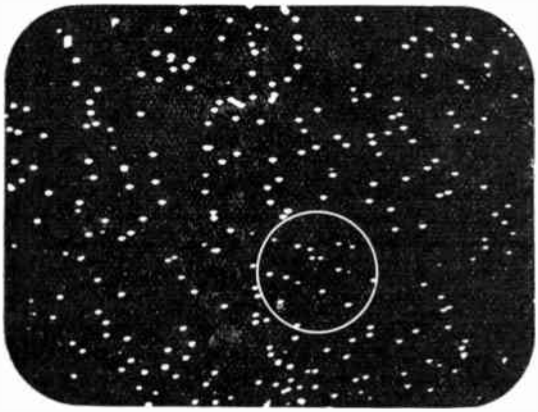


Fig. 5.—Raster in which the electron beam does not pass through the centre of the scanning fields.

In order to examine the spot shape, the usual method is to modulate the C.R.T. with a series of very short pulses of sufficient amplitude to modulate the beam from black level to peak white. A special waveform generator giving what has been called a "polka-dot" raster can be used, or more simply, a spark gap which can give a display as illustrated. A further method which requires rather more care is to deflect the spot by means of direct currents in the scanning coils.

Various spot shapes can be obtained in the corners of the raster by altering the scanning field shape. It is usual to have some form of coma present which can be attributed to spherical aberration or combined spherical aberration and astigmatism by an argument similar to that used for lens aberrations in optics, although the conditions are not completely analogous.

If the axis of the electron beam does not pass through the centre of the scanning coils or is not parallel to the axis of the scanning coils, focusing asymmetries will be observed on the screen as can be seen on Fig. 5, in which the centre of focus is well below the centre of the raster.

Another form of defocusing which depends upon the scanning field shape is due to the existence of an axial component of scanning field near the ends of the coil. This does not, in general, exist on the axis, as shown in Fig. 6, and if either the beam width or the deflection is increased, the spot size will increase. The effect can be diminished by moving the end turns away from the tube neck although this reduces the efficiency of the scanning coil.

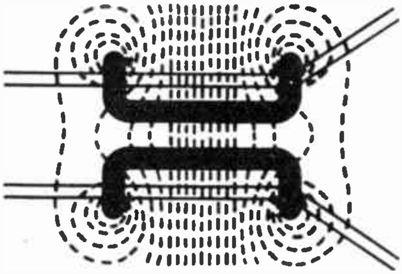


Fig. 6.—Lateral view of a scanning field showing the axial component of field near the end turns.

3. The Focusing Field

A magnetic focusing field such as is used with television tubes is usually considered to be equivalent to a convex lens of focal length,

$$f = -\frac{8\,mE}{e\int H^2 dx} \quad \ldots\ldots\ldots\ldots\ldots\ldots(1)$$

and we should expect the spot size to obey the law of optics

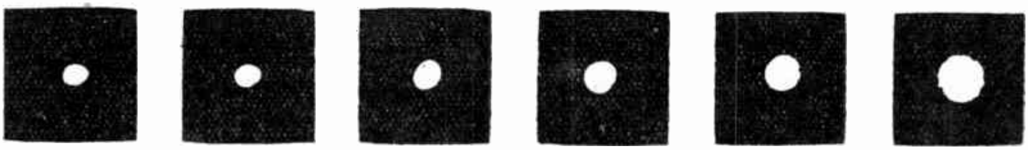


Fig. 7.—Spot size (magnified) for various positions of focus unit. (See Fig. 8.)

$$d_1 = d_0 \cdot \frac{v}{u} \quad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

where d_0 is the diameter of the object (the cathode or grid-cathode crossover), u the object distance, and v the image distance.

Equation 1 is derived by assuming certain conditions to be valid, and if any divergence from equation 2 is observed, it is likely that the divergence is due to a false premise in equation 1. If one or more of the conditions is invalid, it does not necessarily follow that the field is not behaving as a convex lens, but may simply affect the value of f. We should therefore examine the conditions and attempt to estimate their accuracy and the resulting effect on the size of the image.

In order to discover how the results obtained differ from the results expected by equation 2, spot size was measured for different positions of the focusing field. The object distance was taken to be the distance from the cathode to the position of maximum focus field and the origin of the electron beam, and hence the origin of the graph (Fig. 8), is subject to a certain amount of doubt, although the error should not exceed a few millimetres.

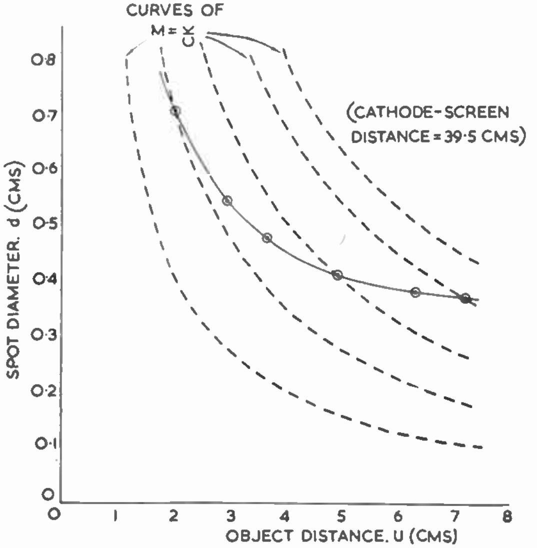
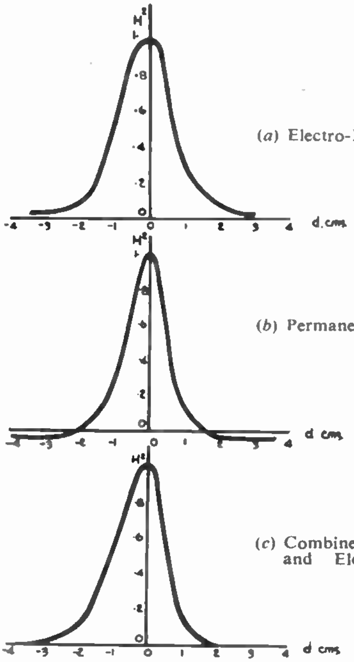


Fig. 8.—Variation of spot size with distance of focus unit from cathode for constant screen illumination. Focusing flux adjusted for best focus.



(*a*) Electro-Magnet

(*b*) Permanent-Magnet

(*c*) Combined Permanent- and Electro-Magnet

Fig. 9.—The field along the axis of various focus units. The electron beam traverses the field from left to right. H^2 is plotted as a fraction of $(H\ max)^2$. d is the distance from the gap in cms.

Since the size of the object is unknown, a single curve for the expected image size cannot be drawn, but a family of curves clearly indicates where the main divergence from equation 2 occurs, namely, when u is large.

The conditions (see appendix) under which equation 1 is derived are as follows:—

(*a*) The field extends a very short distance along the axis being elsewhere negligible.

Figure 9 shows the magnitude of H^2 at points on the axis of three types of focusing device.

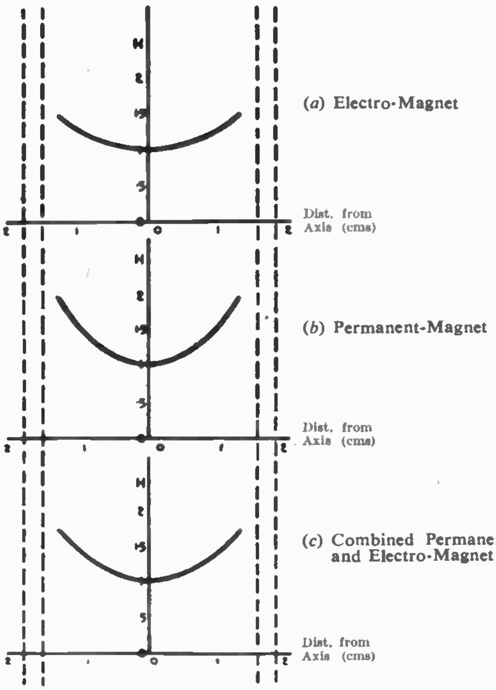


Fig. 10.—*The focusing field across the normal plane containing the gap.*

The curve (*c*) is that of the unit used to obtain the graph, Fig. 8. The curve shows that if the peak of the focusing field is closer to the C.R.T. object than 2 cm, there is likely to be some effect on the focus, the spot being smaller than indicated by equation 2. In the limiting case of the .distance, object to Focus field, being zero, one can obtain some sort of focus. It is not, however, felt that the effect on focus will be very great when the gap of the focus unit is more than 2·5 cm from the object using the components mentioned, since the change in distance from the axis of electrons on the outside of the effective beam is small, being normally less than 4 per cent.

(*b*) The electrons have attained their maximum velocity before encountering the focusing field.

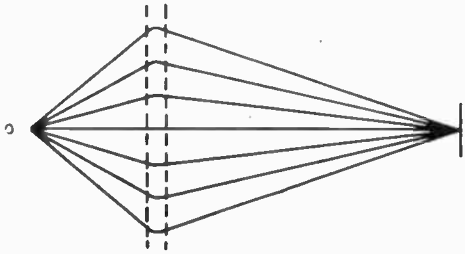
In the experiment resulting in Figs. 7 and 8, the tube used had a spacing (axially) of less than 1 cm between cathode and anode, the anode diameter being approximately 2 cm. It is considered that in the region under examination the assumption that the electron velocity has reached its final value is accurate to a high degree.

(*c*) The angles of convergence and divergence of the beam are small.

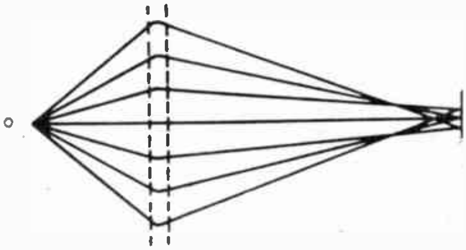
It is difficult to measure accurately the divergent angle of the outside of the useful part of the electron beam but it is probably less than 6 deg. from the axis in normal conditions, in which case the approximation $\cos\theta = 1$ is better than 0·55 per cent.

(*d*) $\int H^2 dx$ is not a function of r. That is, the field is constant at all points on a normal plane.

Figure 10 indicates the sort of variation of the magnetic field to be expected on the normal plane containing the gap, and shows that the condition is by no means valid, especially when the beam width is large (i.e. u large). The effect of such a field is to produce spherical aberration as shown in Fig. 11. We should thus expect the spot size to be greater than predicted by equation 2, the difference increasing with u.



(*a*) H constant over normal plane



(*b*) H increases with distance from axis

Fig. 11.—*Spherical aberration due to variation of focus field across the normal plane.*

(*e*) The direction of H is at all points parallel to the axis.

This condition is, of necessity, invalid, but the assessment of the effect of this situation would indicate that the effect on the focusing merit of the lens is small, provided that the lens thickness is not too great compared with the object distance *u*. The effect of a radial component of the focusing field is to deflect a paraxial electron towards a direction at right angles to the radial direction in much the same manner as the ordinary focusing effect, but in this case the electron which is subject to this deflecting force on entering the focusing field will be subject to a similar force in the reverse direction on leaving the field.

4. The Adjustment of the Position of the Focus Unit

It is assumed that the deflector coils have been designed to give the minimum amount of deflection defocusing, and that the magnitude of the E.H.T. potential is fixed.

Since the design of the focus unit and its position are interdependent, it is not possible to have a final design of unit before deciding upon the position, but experience will indicate the approximate design which will be required.

The position of the experimental focus unit is adjusted to give the best overall focus. If the corners of the raster are defocused, but the centre is sharply in focus, the unit is too far forward; if the focus is poor all over the picture, the unit is too close to the cathode, and the resultant magnification too large. When the optimum position is being approached, care must be taken to ensure that the beam is passing through the centre of the scanning coils.

When the optimum position has been found, attention should be paid to the focus field shape, remembering that, if the object distance is large, the field should be as constant as possible in the normal plane, which implies that a wider gap should be used than when the object distance is small.

The focus unit will now have to be modified and the size and material of the permanent magnet or the number of turns and volume of wire of an electromagnet can be decided.

The optimum position of this new unit can then be found and final checks on the focus unit design made.

5. The Focus Control

The focusing field required by a receiver depends upon:

(*a*) the position of the focus unit,

(*b*) the magnitude of the E.H.T. potential,

(*c*) the dimensions of the tube.

It is possible that from one receiver to another of the same design, these conditions may vary. The field produced by a given focus unit may also vary due to:—

(1) mechanical tolerances,

(2) magnitude of M.M.F.

There may also be a variation of conditions (*b*) and (2) from time to time, due, for example, to changes in mains potential. The focusing control available to the viewer for covering these variations will usually be different from the control which is intended to cover production tolerances.

It has been found, in practice, that it is possible to hold the focus unit tolerances to a fairly high degree of accuracy, but owing to the limitations of the mechanics of holding cathode ray tubes, and variation in the size of tubes, it is difficult to ensure that the unit is in the correct position. If, however, the E.H.T. potential does not vary from receiver to receiver to any great extent, and if, in fact, conditions (1) and (2) are not subject to material variation, then the correct position of the focus unit can be found merely by moving it until the picture is in focus. This method has been used successfully, and when tests have been made to determine the difference between the focus unit position and the position given by working through the process described in Section 4, the difference has never been great enough to cause any fear that the best results are not being obtained.

In many cases, however, this method is unsatisfactory because the E.H.T. potential may vary from set to set, and unless the E.H.T. is supplied from the mains, or from a stabilized supply, it cannot be recommended. The focus unit position should first be fixed. If the mechanical arrangement precludes the possibility of automatic accurate positioning, then some manual adjustment should set the position at a fixed distance from the scanning coils, and the focus should be achieved by varying the field produced by the focus unit. A better method, but one which is normally not possible, is the adjustment of the E.H.T. potential to the nominal value.

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The viewer control should normally be a control of the focus unit field, unless a mains-compensated focus unit is being used, in which case a control is not necessary. In the case of an electro-magnetic unit, this is done by varying the coil current. In the case of a permanent magnet unit, the best method is to have an auxiliary coil through which the current is variable. The most commonly used device is the variation of the gap of the unit, but there is little to recommend it, since the shape of the field is altered, and the adjustment is in most cases difficult and irritating to the viewer.

6. The Effect of Supply Potential Variation

Should the mains supply to a receiver change, unless precautions are taken, the focus may be so affected as to become intolerable, and where pre-set focus is used, as in the case of permanent magnet devices, the effect is distressing to the viewer.

If the E.H.T. is derived from the mains, the E.H.T. potential E, will be proportional to the mains potential V, and the focal length of the focusing lens,

$$f \propto V$$

$$\text{i.e.} \quad \frac{\delta f}{f} = \frac{\delta V}{V} \quad \ldots\ldots \text{Permanent Magnet.}$$

If the focusing field is derived electrically such that $\int H^2dx \propto I^2$ and $I \propto V$, then

$$f \propto \frac{1}{V}$$

$$\text{i.e.} \quad \frac{\delta f}{f} = \frac{-\delta V}{V} \quad \text{(approx.)} \quad \ldots \text{Electro Magnet.}$$

If half the focusing field is derived electrically, and half from a magnet such that $\int H^2dx \propto V$ (approx.), then

$f =$ constant (approx.) . . Combined Focusing.

When the E.H.T. potential is derived from an oscillator or the line-flyback, E may not be proportional to V, in which case the combined focus unit is adjusted such that $\int H^2dx \propto E$ as far as is possible.

Experiments have been carried out which involve using current from the scanning efficiency diode to provide part of the focusing field, since this current is reduced when the supply voltage is reduced, but this scheme has the disadvantage of interdependence of controls.

In the design of a mains compensated focus unit in which a magnet encloses a coil, a situation frequently arises where either the physical dimensions become too large or the current in the coil must vary such that $\delta i/\delta V > 1$, where V is the mains voltage, in order to maintain

$$\int H^2dx/E = \text{constant.}$$

This condition usually occurs when triode cathode ray tubes with large E.H.T. potentials are used, being due to the fact that the focusing flux required is large, and a coil to supply half this flux is also large. This, in turn, implies that the magnet is large, although inferior magnetic material can be used, and the magnet need not be particularly expensive.

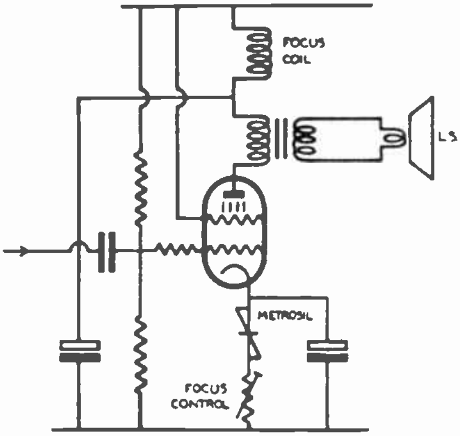

Fig. 12. Method of increasing the variation of focus current with mains voltage.

Circuits have, however, been evolved which fulfil the alternative condition that $\delta i/\delta V > 1$ at the same time ensuring that the focusing current does not vary appreciably as the temperature of the coil rises and the resistance increases.

In the circuit illustrated in Fig. 12, a valve, usually the sound output valve, is used as a d.c. amplifier in addition to its normal function, the d.c. input being dependent upon the H.T. potential.

7. The Effect of E.H.T. Supply Internal Impedance

When a television picture is focused with a small beam current, but shows general defocusing even in dark portions of the picture when the beam current is increased, the cause is

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probably the drop in E.H.T. potential due to the internal impedance of the power supply. This effect does not occur, in general, in the case of a mains power supply, but when the E.H.T. is derived from the line fly-back, or from an oscillator, great care must be taken to ensure that the regulation is adequate.

The figure of merit of such a power supply is derived in Appendix 2:—

$$\frac{E^2}{\delta E/\delta i}$$

where E is the E.H.T. potential off load, and $\delta E/\delta i$ is the internal impedance.

Thus a potential of 10 kV through an impedance of 10 MΩ will produce the same amount of defocusing as 8 kV through an impedance of 6·4 MΩ.

In the design of a receiver, it is possible, having decided upon the tube and focus unit position, to decide upon the figure of merit required of the power supply.

The table shows figures measured using a standard focus unit with triode tubes.

	9″ tube.	12″ tube.	15″ tube.
Intolerable Regulation	below 4	below 6	below 9·25
Tolerable Regulation	4–8	6–14	9·25–22
Good Regulation	above 8	above 14	above 22

The normal circuit, using the line fly-back pulse to generate E.H.T. in the range 6-12 kV, has been found to have a figure of merit in the range 7-20. The inclusion in the circuit of a component which has a negative coefficient of resistance with current such as a "Metrosil," has been found to give figures of merit up to 25.

In certain cases, particularly when an oscillator type of supply is being used, it is possible to stabilize the potential by means of a feedback circuit. This is particularly useful in the generation of high potentials for projection tubes, but tends to add considerably to the cost of the receiver concerned.

Appendix 1.—The Focus Equation

The Focus Equation is well known but the derivation is included here for reference purposes. The simple vector method of solution is not employed, since many engineers are not familiar with this branch of mathematics, but the following does involve the use of cylindrical co-ordinates in which

angular velocity $v_\phi = r\dfrac{d\varphi}{dt}$,

radial velocity $v_r = \dfrac{dr}{dt}$,

angular acceleration

$$a_\phi = \frac{1}{r}\frac{d}{dt}\left(r^2\frac{d\varphi}{dt}\right), \text{ and}$$

radial acceleration

$$a_r = \frac{d^2r}{dt^2} - r\left(\frac{d\varphi}{dt}\right)^2.$$

e and m are the charge and mass of an electron which is subject to an axial magnetic field H.

The force acting in a radial direction.

$F_r = a_r m = -eHv_\phi$

The force acting at right angles to r

$F_\phi = a_\phi m = eHv_r$

$$\text{But } a_r = \frac{d^2r}{dt^2} - r\left(\frac{d\varphi}{dt}\right)^2 = -\frac{e}{m}Hr\frac{d\varphi}{dt} \quad (1)$$

$$\text{and } a_\phi = \frac{1}{r}\frac{d}{dt}\left(\frac{r^2 d\varphi}{dt}\right) = \frac{e}{m}H\frac{dr}{dt}$$

$$\therefore \frac{d}{dt}\left(r^2\frac{d\varphi}{dt}\right) = \frac{eH}{2m}\cdot\frac{d}{dt}(r^2)$$

$$\text{i.e. } \frac{d\varphi}{dt} = \frac{eH}{2m}$$

Substituting this in equation 1

$$\frac{d^2r}{dt^2} - \frac{r\,e^2H^2}{4m^2} = -\frac{e^2\,rH^2}{2m^2}$$

$$\text{i.e. } \frac{d^2r}{dt^2} + \frac{re^2H^2}{4m^2} = 0$$

This must be expressed in terms of x, the axial distance along the C.R.T.

$$\frac{dr}{dt} = \frac{dr}{dx}v_x. =$$

$$\text{and } \frac{d^2r}{dt^2} = \frac{d^2r}{dx^2}(v_x)^2 \ldots\ldots\text{if } \frac{dv_x}{dt} = 0$$

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$$\therefore \frac{d^2r}{dx^2} + \frac{re^2H^2}{4m^2(v_x)^2} = 0$$

But $$v_x = \sqrt{\frac{2Ee}{m}}$$

$$\therefore \frac{d^2r}{dx^2} + \frac{reH^2}{8mE} = 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

This is the general equation, to which we now apply the conditions associated with a thin lens.

Let $P = \frac{1}{r_0}\frac{dr}{dx}$

and let $r = r_0$, i.e. constant within focusing field. Equation 2 reduces to

$$\frac{dP}{dx} + \frac{eH^2}{8mE} = 0$$

$$\text{i.e. } P_b - P_a = -\frac{e}{8mE}\int_a^b H^2dx$$

$$= \frac{1}{f}$$

$$\therefore \quad f = -\frac{8mE}{e\int_a^b Hdx} \quad \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Appendix 2.—Figure of Merit for E.H.T. Supply

From Appendix 1 we see that

$$f \propto E$$

A measure of the defocusing for change in E.H.T. is

$$\frac{\delta f}{f} = \frac{\delta E}{E} = \frac{\frac{\delta E}{\delta I}\cdot\delta W}{E(E-\delta E)}$$

Where δE is the drop in potential due to current δi, and screen dissipation is

$$\delta W = \delta i\,(E-\delta E).$$

Thus, for a given focusing field and tube, we can write a "Goodness Factor" for the E.H.T. supply.

$$\frac{E\,(E-\delta E)}{\delta E/\delta i}$$

In order to eliminate the necessity of defining δW, we can write, to a first approximation.

$$\text{Figure of Merit} = \frac{E^2}{\delta E/\delta i}$$

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NOTICES

Annual Radio Industry Dinner

The Radio Industry Council now organizes an annual radio industry dinner. This year's dinner will be held at the Savoy Hotel, London, on Tuesday, November 25th, when H.R.H. the Duke of Edinburgh, K.G., will be the guest of honour.

As announced at the last Annual General Meeting (October 1951 *Journal*), His Royal Highness is an Honorary Member of the Institution.

Co-option to the General Council

Commander H. F. Short, R.N., M.B.E. (Associate Member), who was elected a member of Council in 1950, has recently been posted overseas. Council has therefore co-opted Lieutenant-Commander J. R. Christophers, R.N. (Associate Member), to serve for the remaining months of Commander Short's period of office.

Lieutenant-Commander Christophers at present holds an appointment at the Admiralty in London, and he was previously an Instructor Officer on radar in H.M.S. "Collingwood." A brief biography of Commander Short was published in the July 1950 issue of the *Journal.*

The University of Southampton

The Council congratulates the authorities of University College, Southampton, on obtaining a Royal Charter and becoming an independent university with the power to confer degrees.

The Institution has always been closely associated with the college through its post-graduate courses in Electronics. Professor E. Zepler, who holds the chair in Electronics, is a member of Council and Chairman of the Education and Examinations Committee. (See February 1950 *Journal.*)

Mr. J. L. Thompson

Members will be interested to learn that Mr. J. Langham Thompson (Member), Chairman of Council, has recently left England on a three months business trip around the world, in the course of which he will visit India, Pakistan, Australia New Zealand, the United States and Canada.

During his stay in India Mr. Thompson visited the Delhi and Calcutta Sections of the Institution and he was able to give the local committees advice and guidance for their early work. Mr. Thompson will also meet the local section in New Zealand, as well as local representatives and members in various Commonwealth countries and the U.S.A.

A note on Mr. Thompson appeared in the *Journal* for April 1950.

London—Paris Television Link

An exchange of programmes between London and Paris has been planned for the week July 7th to 14th. Members of the Institution have already been invited to visit the French transmitters and studios during this Anglo-French week.

In addition, the Editor of the French journal *Television*, Mr. A. V. J. Martin (Associate Member), together with other members in France, would be pleased to welcome an Institution party. A provisional programme of meetings has been prepared for July 10th to 13th.

Members wishing to join this party are invited to advise the Secretary by June 10th, when details will be available of transport, hotel accommodation and other arrangements.

Long-Playing Gramophone Records

The recent announcement by Electric and Musical Industries, Ltd., of its intention to introduce long-playing, microgrove records foreshadows lively competition in this field. Hitherto, the Decca Record Company has been virtually the sole manufacturer of long-playing records in this country, and it has also built up a substantial export business.

There has been no statement as to whether the E.M.I. Group will adopt the 33⅓ r.p.m. or the 45 r.p.m. standard, or both. Neither has there been any announcement of the production of dual or triple speed radiograms.

Discussing this announcement, a correspondent of the *Financial Times* referred to the spectacular public response to the introduction of L.P. records in the United States. In the three years in which microgroove records have been on sale there, the range of recorded music has grown beyond recognition. There are some 60 to 70 companies now recording, and intense competition prevails; this has caused record companies almost to give away classical recordings made on standard shellac discs (78 r.p.m.).

In these circumstances, the publication in this issue of the *Journal* of the 1951 Radio Convention paper on "Microgroove Recording and Reproduction" by Mr. E. D. Parchment (Associate), will be of particular interest.

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OVERSEAS NOTICES

Broadcasting in India

Before leaving Delhi in February, Mr. G. D. Clifford broadcast from the New Delhi Station of All-India Radio on the development of radio in India.

In the course of his observations, Mr. Clifford referred to the achievements of the Indian radio industry: during 1951 150,000 radio receivers were sold of which no fewer than 140,000 were actually assembled in India.

Mr. Clifford said that the aim of the industry would be to become as self-sufficient as possible and steps were now being taken to develop sources of raw materials. Already a number of manufacturers were considering manufacturing their own components, which in time would lead to cheaper radio sets. He stressed that there must be sufficient demand to permit reasonable production.

To date, radio licences in India only totalled half a million and All-India Radio possessed the monopoly of broadcasting. Mr. Clifford suggested that the small demand for sets with only a medium wave coverage showed either dissatisfaction with local programmes or a desire to listen directly to events outside India, and he urged some form of listener research to assist both the broadcasting authority in the design of programmes and the radio industry in the production of sets.

Centennial Congress of Engineering in the U.S.A.

Under the ægis of the Organization for European Co-operation in conjunction with the United States Mutual Security Agency, a number of engineers are being invited to take part in the Centennial Congress of the American Society of Civil Engineers.

It is understood that 200 foreign engineers will be invited to attend this Congress, which will be held in Chicago between September 3rd and 13th, 1952, and that a programme of visits by specialized groups, consisting of approximately 15 members, is planned for a period of three weeks after the close of the Congress.

The Organization for European Co-operation proposes to organize a Technical Assistance Mission. Under these arrangements, institutions and associations would have to bear the cost of their nominees' travel to and from the United States, but travel and subsistence whilst in the U.S.A. would be found by the U.S. authorities in accordance with normal arrangements for missions of this nature.

In order to qualify for E.C.A. financial help to attend the Centennial, it is necessary that the teams should be made up of professional engineers. The definition of a professional engineer is quoted as follows:—

"A professional engineer is competent by virtue of his fundamental education and training to apply the scientific method and outlook to the solution of problems, and to assume personal responsibility for the development and application of engineering science and techniques especially in research, designing, manufacturing, superintending and managing. His work is predominantly intellectual and varied, and not of a routine mental or physical character but requires the exercise of original thought and, if necessary, the responsibility for supervising the work of others, including that of engineering technicians.

"His education will have been such as to make him capable of closely and continuously following all progress in his branch of engineering science by consulting newly published works on a world-wide basis, assimilating this information and applying it independently. He must be able to make contributions to the development of engineering science and its applications.

"By virtue of his education and training he will have acquired a broad and general appreciation of the engineering sciences as well as a thorough insight into the special features of his own branch, with the result that in due time he can give authoritative technical advice or be responsible for the direction of important tasks in his branch."

Canada-U.S.A. Radio Telephony Agreement

A treaty has recently been signed between Canada and the United States establishing a uniform system of marine radio telephony, with the object of promotion of safety of life and property on the Great Lakes and as an aid to navigation.

The agreement provides for the authorized use of radio telephony as a means of communication of distress signals for shipping on the Great Lakes, with the distress frequency (2182 kc/s) and the present working frequencies being continued. It further agrees on the need for making compulsory the carriage of radio telephone equipment on all lake shipping of 500 gross tons and over, and on all passenger-carrying vessels over 65 ft. in length.

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SOME ASPECTS OF MAGNETIC SOUND RECORDING*

by

O. K. Kolb, Ph.D.†

A Paper presented at the Sixth Session of the 1951 *Radio Convention on September 4th at Earls Court, London*

SUMMARY

The development of magnetic sound recording from the end of the last century to the present day is described, more particularly from the aspects and results of the introduction of the oxide-coated tape by Pfleumer and the magnetizing or biasing of this tape with a supersonic frequency by Braunmühl and Weber. The extension of these developments which has taken place since the war, especially in Great Britain and the U.S.A., is referred to and the improved effect of biasing with a supersonic frequency is dwelt upon. The explanations advanced by research workers such as Wetzel and Montani for the improvement obtained by high frequency biasing are considered and discussed at considerable length, and a more detailed explanation is advanced. Finally, the paper deals with some aspects of signal erasure utilizing a.c. mains and high frequency currents.

1. Early History

In 1888, in a periodical called *Electrical World*, Oberlin Smith discussed for the first time the possibility of using permanent magnetic impressions for the registration of sound. His idea was to spin or to weave small magnetic particles such as steel dust or short lengths of fine steel wire into a cotton or silk thread. He proposed this type of material because he considered it would be superior for magnetization purposes to a continuous steel wire which he thought would not sub-divide into a plurality of short magnets of varying strength. He had this idea because the conception of magnetism in those days was that magnetic poles of equal and opposite polarity would merely appear at each end of a steel bar or steel wire and that if this bar or wire were broken into short pieces a number of small magnets all of equal strength would be obtained. Therefore, he suggested the use of a magnetic recording medium of discontinuous small particles.

2. Telegrafone

In 1898 Valdemar Poulsen investigated the possibility of magnetizing limited areas of a steel element which was sufficiently hard to prevent the magnetization from spreading to its ends. For this purpose he took a steel plate and moved a magnet across it in an attempt to write letters in a similar manner to that in which one writes chalk letters on a blackboard. Subsequently, he sprinkled iron filings on the plate and found that the iron filings adhered only to those parts of the plate across which he had moved the magnet. In this way he was able to show that magnetization was possible at individual points. This led him to the idea of magnetizing a continuous hard steel wire with a magnetic field fluctuating in accordance with the variations of sound waves to be recorded.

Poulsen's discovery and his Telegrafone, the name which he gave to his magnetic wire sound recorder and reproducer, caused a considerable sensation at the time, but did not result in the universal application of the Telegrafone for sound-recording purposes, chiefly because other methods of recording such as the disc and photographic film came to the fore and reached a much higher standard of perfection.

3. New Developments

This position remained virtually unaltered until the last war, during which, as a result of new developments, considerable advances were made in Germany and extended thereafter, especially in Great Britain and the U.S.A. As a consequence magnetic sound recording came into prominence again and now appears likely to gradually supersede all other existing sound-recording methods where high quality is the principal essential.

This change was brought about by the combination of two ideas, the first of which was that of using an oxide coated tape as the sound record carrier, and secondly, that of magnetizing or biasing this tape with a supersonic frequency.

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* Manuscript received August 23rd, 1951.

† British Acoustic Films, Ltd.

U.D.C. No. 621.395.625.3.

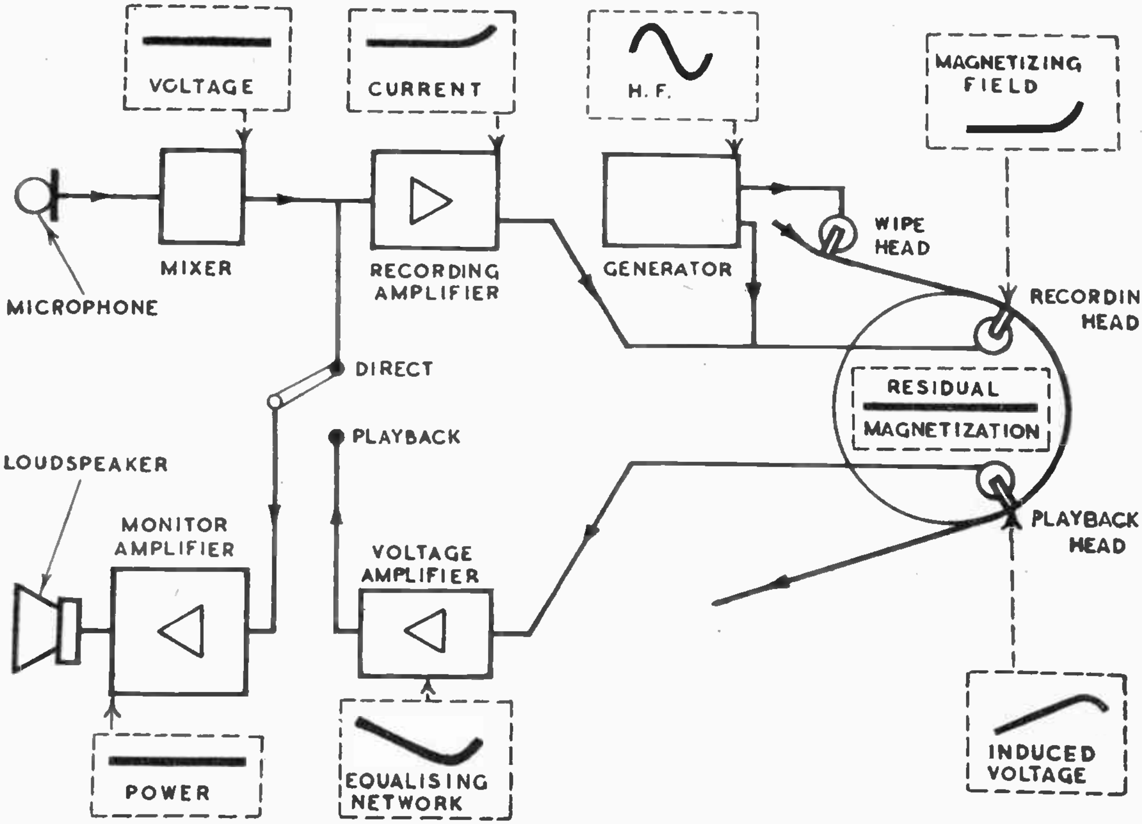

Fig. 1.—Layout of magnetic sound-on-film equipment.

A sound record carrier in the form of an oxide-coated tape was first introduced in 1928 by Pfleumer.[1] The oxide-coated tape was found to be superior to the steel wire or tape in many respects and led Volk[2] to construct what was, in effect, the first Magnetophone.

The outstanding advance by magnetic recording over all previous recording methods was, however, made by Braunmühl and Weber[3] who, in 1940, were the first to magnetize or bias Pfleumer's tape with a supersonic frequency.

Poulsen[4] had used his Telegrafone with d.c. premagnetization or bias, and Carlson and Carpenter[5] had applied an a.c. bias to the steel wire or tape of the same instrument, but it was not until Braunmühl and Weber applied a high frequency bias to the oxide-coated tape that it was possible to obtain a quality with magnetic sound recording comparable and even superior to other sound-recording means. This will be appreciated from the fact that with the tape running at the reasonable speed of approximately 30 in per sec it was possible to obtain a frequency response up to 20,000 c/s.

Immediately after the war the development of magnetic sound recording employing high frequency biasing was extended to the sound film industry, in particular, in this country and the U.S.A., and a short general description will now be given of the layout of a magnetic sound-on-film equipment which has been developed by British Acoustic Films.

4. General Circuit Arrangement

The general layout of the magnetic sound-on-film system is illustrated schematically on Fig. 1. The signal current created by the sound impinging upon the recording microphone is

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passed on to a voltage amplifier and mixer having a straight line response, after which it is fed to a recording amplifier having a pre-emphasizing characteristic compensating for losses, particularly of the higher frequencies, incurred in the transfer of the signals from the magnetic recording head to the magnetic sound-film.

A supersonic frequency from a high frequency oscillator is fed into the recording head and, at the same time, the oscillator also conveniently supplies an erasing head placed in such a position that the magnetic sound-film passes it before reaching the recording head.

The curve shown above the recording amplifier block illustrates schematically the pre-emphasis to which the signal current is subjected prior to the actual recording step, so that the signals recorded on the sound carrier have an almost straight line frequency characteristic.

The magnetic sound-film on which the magnetic layer is now magnetized passes round the recording drum to a second, playback, head, which can be used either for reproducing or for monitoring while recording takes place.

As the frequency characteristic of the signals picked up from the film is not, however, straight, it has to be equalized by the inverted characteristic of a special equalizing network and voltage amplifier, the output of which is passed to a monitor and power amplifier feeding the reproducing loud speaker.

In order to adjust the equipment and, also, for purposes of comparison during recording, a change-over switch is provided by means of which the signals from the microphone amplifier and mixer can be fed either directly to the monitor power amplifier and the loud speaker, or, alternatively, via the recording amplifier and head, record carrier, reproducing head and amplifier to the same power amplifier and loud speaker. If the apparatus is properly adjusted there will be, or should be, no audible difference between the sound from the loud speaker reproduced directly and that played back through the magnetic recording and reproducing channel in a magnetic sound-film system incorporating high frequency biasing.

As already mentioned the greatest advance in the quality of magnetic sound recording was due to the incorporation of supersonic frequency biasing in the recording process.

The functioning of the H.F. recording bias, however, was not immediately understood, and several possible explanations of its operation and the manner in which it produces a linear transfer characteristic have been given. Some of these views will now be outlined, commencing with the effect of recording with no bias.

5. Recording with no Bias

In a magnetic field iron behaves in a peculiar manner and its behaviour is characterized by a hysteresis curve. In a magnetic sound-film system the magnetic field is usually applied by means of a ring-shaped magnetic head consisting of a laminated iron core having a small gap and one or two magnetic field coils wound on the core.

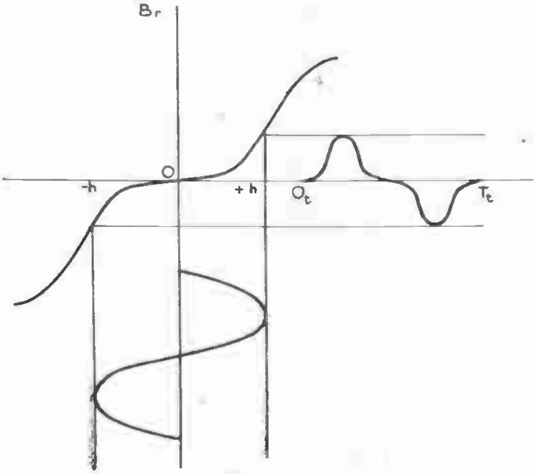

Fig. 2.—Remanent induction versus magnetizing force.

When a magnetized iron particle on the film is removed from the exciting field created by the head a certain amount of residual induction is left in the particle and the value of such remanent induction plotted against the magnetizing force of the field is illustrated by the *Br* curve on Fig. 2.

If a recording is made without any biasing it will be appreciated that any attempt to vary the magnetic field to record on a medium with such a transfer characteristic will result in severe amplitude distortion of the recorded signal as the *Br* curve is not linear but starts with a very flat portion round the zero point followed quickly by a sharp bend and, for large fields, considerable curvature at both ends.

To illustrate this to better advantage there is also shown on Fig. 2, in addition to the *Br* curve, the recorded characteristic of an audio frequency signal of sinusoidal shape which shows that when the exciting field varies between the values $+ h$ and $- h$ the resultant curve will be between the values $+ Br$ and $- Br$. When the amplitude of the signal to be recorded increases rapidly from zero there will be no corresponding rapid response in the transfer characteristic for a considerable period and a recorded signal with a large harmonic distortion content will result.

6. Recording with D.C. Bias

Poulsen was aware of this with his Telegrafone, and even at that early date had attempted to linearize the transfer of the signal by moving the operating point from the zero point to another point on the transfer curve where the curvature is at a minimum and could be approximated to a straight line. This he did by pre-magnetizing his steel wire record carrier with d.c., which had the effect of lifting the superimposed audio frequency signal to the desired point at the centre of the substantially linear part of the transfer characteristic.

Unfortunately, with pre-magnetization or biasing with d.c. the linear part of the transfer characteristic is not very extensive and it will be appreciated that only a small amplitude range can be covered by this method without incurring considerable distortion.

To obtain a tolerable result with D.C. biasing it is, therefore, necessary to operate over very small parts of the transfer curves in order to eliminate as much distortion as possible. Unfortunately, the effect of doing this decreases the signal-to-noise ratio because the d.c. bias pre-magnetizes the magnetic particles in the recording medium and the irregularities in the distribution of these particles in a tape or film contributes to a quite considerable amount of background noise.

7. Supersonic Bias

These difficulties were overcome by the introduction of a.c. biasing which eliminated distortion and reduced background noise to such a considerable extent that it was only natural that much speculation as to the manner in which the supersonic bias operated took place.

One of the first possible explanations advanced was that the high frequency excitation acted as a sensitizer and created an agitation of the magnetic particles in a manner which enhanced their linear registration.

8. Wetzel's Explanation of h.f. Biasing

Another explanation was put forward by Wetzel[6] and has been accepted very generally.

To explain Wetzel's theory the transfer curve *Br* is taken and a supersonic biasing frequency is allowed to move between the values $+ h$ and $- h$ (Fig. 3). The audio frequency current is then added to the supersonic bias current. A lateral shift dependent on the amplitude of the audio frequency will then take place between the amounts $(h + a)$ and $- (h + a)$.

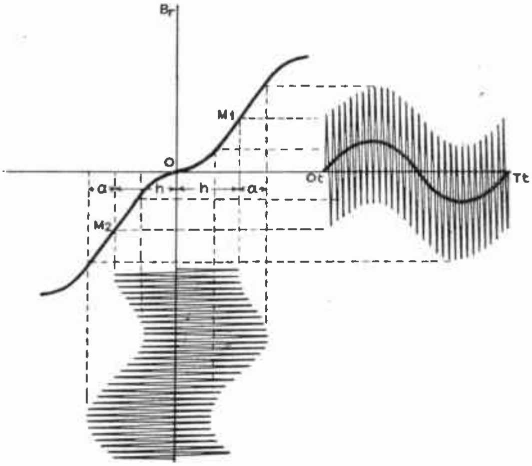

Fig. 3.—Transfer curve illustrating Wetzel's theory of h.f. biasing.

It will be observed that the amplitudes of the high frequency bias current $+ h$ and $- h$ are so chosen that their remanent *Br* values are placed in the middle of a substantially linear part of the *Br* curve. By plotting the maximum values of $h + a$ against time along the vertical axis the maximum values of *Br* can be traced as a function of time along the horizontal axis.

Wetzel assumed that the recording medium is demagnetized at the bias frequency and that the remaining induction is obtained along the two opposite branches of the transfer curve and is recorded on the medium almost simultaneously.

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Wetzel further assumed that when the audio signal was zero, for example in intervals between the sequence of signals, the values of the negative and positive halves of the high frequency bias cancelled each other out and thereby resulted in the very low noise level obtained with such biasing.

There are considerable grounds for assuming this explanation to be correct because the use of the supersonic bias does, in fact, reduce the background noise in the intervals between signals compared with d.c. biasing. Nevertheless, a more recent explanation which seems even more feasible has been put forward by Montani.

9. Montani's Explanation

Montani's[7] explanation is illustrated by Fig. 4. This is similar to Fig. 3 with the difference, however, that the *Br* curve is shown in its rather more accurate shape, that is to say, with no really straight stretches.

If a supersonic biasing frequency is again superimposed on this curve between the point $+h$ and $-h$ and an audio signal current (a) is added to it, the maximum lateral shift will occur between point $+(h+a)$ on one side and point $-(h+a)$ on the other side.

If, now, the varying values of $h+a$ are plotted against time along the vertical axis the resulting values of *Br* can again be traced as a function of time along the horizontal axis.

If it is again assumed that the recording medium will be demagnetized at the bias frequency the remaining induction will be obtained along the two opposite branches of the transfer curve at points M1 and M2. In this case, however, the transfer curve has no straight parts on either side of the point M1 and M2. Consequently, the curve obtained from a sinusoidal input signal will be distorted and it will be observed at the point M1 that the recorded signal grows more rapidly with the positive half-wave and shows a higher amplitude than the negative half-wave, whilst exactly the opposite effect occurs at the point M2 where the positive half-wave is smaller than the negative half-wave.

It is apparent, therefore, that the increase in the positive half-wave at one transfer point is greater than the corresponding positive increase at the other transfer point.

However, if the value of the positive increase of the signal at the point M1 occurs more rapidly in proportion than the increase in the value of the positive signal at the point M2 then, under certain circumstances, a final undistorted signal will occur, namely, if the increase at M1 occurs more rapidly than the increase at M2 occurs more slowly in proportion. The average increase will then be linear and this is the case if the two transfer points M1 and M2 are located on parts of curves which are parabolas or second degree functions.

To illustrate this the point M2 has been superimposed on the point M1 and the negative portion of the transfer curve has been drawn on either side of the superimposed point.

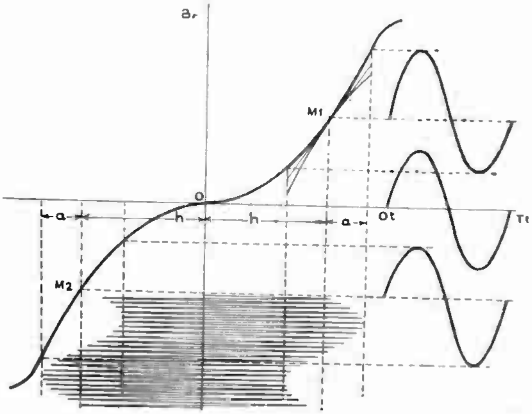

Fig. 4.—Transfer curve illustrating Montani's theory of h.f. biasing.

It will be noted that as the positive branch of the transfer curve increases the negative branch also increases but more slowly. The opposite is the case if the amplitude decreases at the transfer point. The average increase, therefore, lies between the two curves and this increase can be indicated by a straight line if the conditions are such that both curves through the point M1 can be represented by a second degree function.

The conditions illustrated are, in fact, such, and the resultant audio signal has been drawn along the horizontal axis Tt, starting from the point Ot, showing that a signal without distortion will result.

This explanation of Montani's seems to correspond more to reality and to agree with practical results, since, in fact, no part of the *Br* curve is absolutely straight.

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Montani's explanation has a certain resemblance to the class B push-pull operation of two thermionic valves. There is, however, a difference. In the case of the class B push-pull operation the transfer curves are split at the point of origin and the audio frequency input signal is simultaneously applied to both curves. In magnetic recording the *Br* curve cannot be split and, therefore, the supersonic frequency is used to split the audio frequency input signal into two parts, both of which are then virtually simultaneously applied to both branches of the transfer curve.

From the viewpoint of fidelity, therefore, it would seem that the best recording condition and the most suitable material is that having the most extended portion of the transfer curve which can be approximated with the second degree function.

There are, of course, some objections to the above-mentioned explanations, perhaps the most important being the theory that demagnetization of the magnetized particles occurs at the *Br* transfer curve of the supersonic frequency.

A possible explanation which will meet this objection is the assumption that the supersonic frequency is recorded as well as the audio frequency signal. Experiment shows that this is actually the case. Consequently, it can be assumed that what actually takes place on the magnetic sound record carrier is the recording and magnetization of a succession of small magnets (i.e. particles) at the supersonic frequency which combine together to form the audio frequency signal during the reproduction process when this is carried out at the same speed, or substantially the same speed, as the recording operation.

This means that the small magnets created at this supersonic frequency immediately combine and form the comparatively larger audio frequency magnets with the result that the demagnetization factor of the resulting larger sized audio frequency magnets is correspondingly smaller.

10. Approximation by 3rd and 5th Degree Curves

Before leaving this interesting subject of high frequency biasing, mention should be made of an attempt quite recently by Zenner[8] to approach the subject mathematically by approximating the true *Br* curve and resorting to a mathematical series.

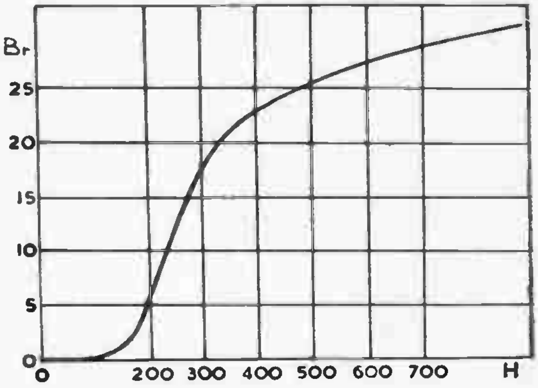

Fig. 5 (a).—Br-H curve for wire No. 449.

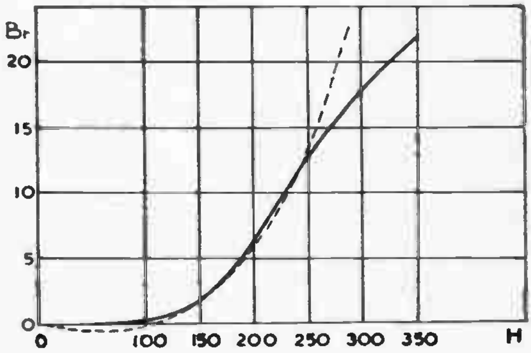

Fig. 5 (b).—Third-order fit to the Br-H curve.

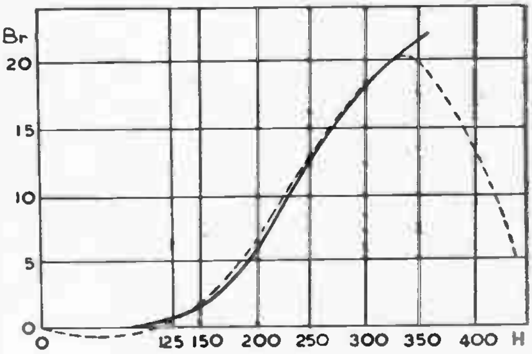

Fig. 5 (c)—Fifth-order fit to the Br-H curve.

On Fig. 5, it will be seen that his assumption is expressed in the mathematical equation:—

$$Br = -K_1H + K_2H^3 - K^3H^5$$

and, in this formula,

$$H = A \sin at + B \sin bt$$

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This means that the field is composed of the two components constituted by the audio signal and the H.F. bias.

By taking the first two members of this equation and applying them to Fig. 5*a*, which is the *Br* curve actually measured for a certain material, there results a fit to this *Br* curve, shown by the dotted line in Fig. 5*b*. You will see that this fit is quite good for a large portion of the *Br* curve.

However, by taking the next member of the series, that is, the fifth degree member of the equation, an even better fit is obtained, as is illustrated in Fig. 5*c*.

By these means, the true *Br* curve can be provided with a good fit by non-linear curves of the third and fifth order, and, as it must be assumed that no part of them is really straight, a certain amount of confirmation of the explanation advanced by Montani is obtained as he was the first to give a rough approximation with a second degree curve.

11. Erasing of Signals

In Section 2 was described how Poulsen had traced letters on a steel plate with a magnet in a similar manner to that in which one writes chalk letters on a blackboard. The analogy goes further since, as is well known, not only can chalk letters be wiped off a blackboard, however thick they are, but magnetically recorded signals can also be erased from a magnetic film, however large the amplitude with which they have been recorded.

This is now done in the most effective way by the use of an alternating current from the mains supply, or from a H.F. generator.

In this apparatus the reel of magnetic film is subjected to a rotary movement which is combined with a translatory movement of a mains energized magnet and its magnetic field. All the particles in the magnetic coating on the film are thus exposed to a strong alternating magnetic field and are gradually, by the combined movement, moved to parts of the field of decreasing strength so that they ultimately leave the field in a completely demagnetized state.

Measurements made during investigations in conjunction with this apparatus have shown that if a signal at a frequency, for example, of 1,000 c/s and of full amplitude is recorded on a reel of magnetic film and the reel is then subjected to the erasing treatment mentioned, the level of the recorded signal will be reduced by more than 80 decibels. This means in practice, of course, that the original 1,000-c/s signal will have disappeared completely if and when the wiped film is played back.

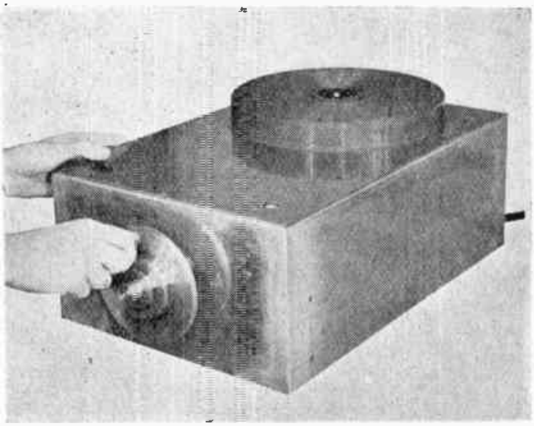

Fig. 6.—Laboratory model of mains bulk eraser.

12. Recording the Bias Frequency

A reel of magnetic film on which a 1,000-c/s note has been recorded at a level 6 db above full modulation is wiped on a mains energized wiper and run through the magnetic soundfilm equipment, previously described, which has been modified by the incorporation of two amplifiers with an attenuation network connected in between in such a way that a maximum attenuation of 80 db can be obtained.

Upon switching on the amplifier a faint noise will be heard which is, of course, the inherent amplifier noise and constitutes a background noise level amounting to approximately −70 db below the level of the reproduced loudness of a signal recorded with full modulation.

Upon the wiped portion of the film being run it will be noticed that this background noise is slightly increased by the noise produced by the film, the noise level will, nevertheless, still be approximately −65 db below the loudness of a reproduced signal of full modulation.

Now upon switching on the recording head and feeding it with a supersonic bias current of approximately 40 mA at a frequency of 50,000 c/s, a further slight increase in background noise will be noticeable and, in fact, we will have arrived at a combined background noise level of approximately −60 db.

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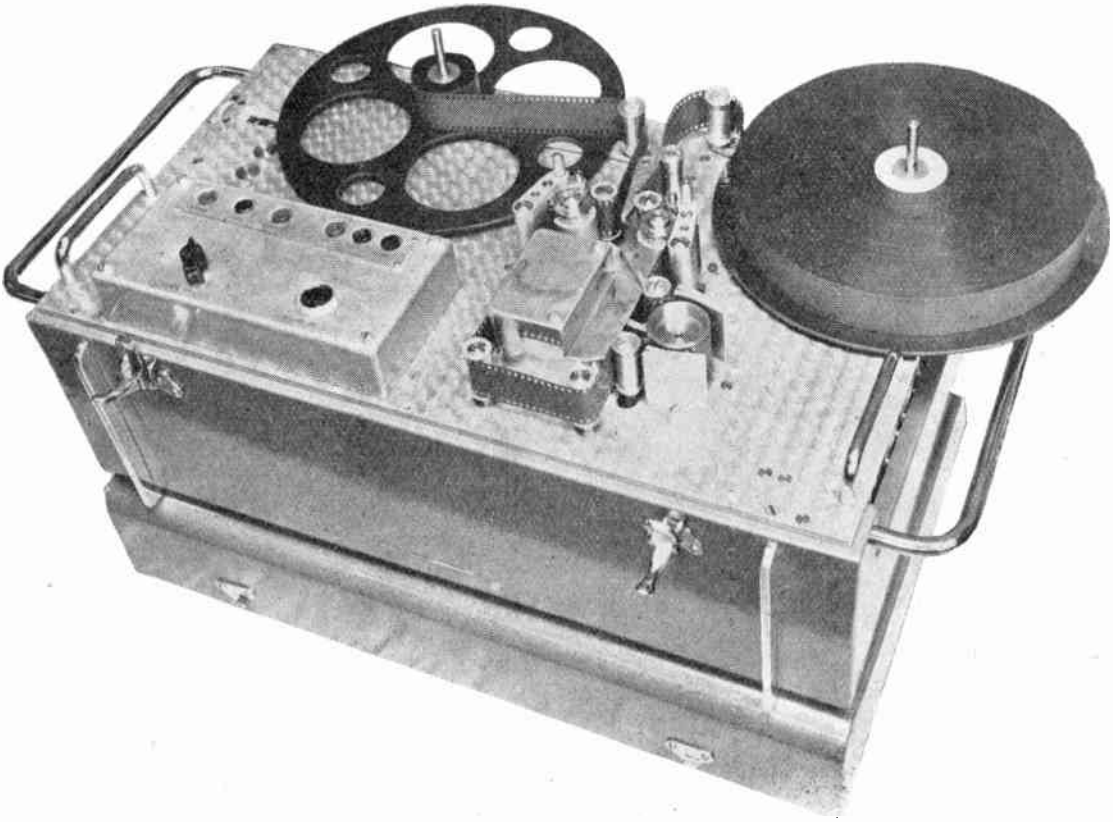

Fig. 7.—British Acoustic "Ferrosonic" magnetic film recorder

By switching off the recording head and switching on the erasing head, no change other than the same slight increase in noise level occurs, which is still at approximately −60 db, and the amount of background noise does not increase any more when the recording and erasing heads are switched on together, so that we have now arrived, as already mentioned, at the lowest combined background noise level of approximately −60 db.

In order to determine to what this slight increase in background noise is due, a current of supersonic frequency, of approximately 30 mA, and again at a frequency of 50,000 c/s, as used in the recording head, is now fed into the erasing head and a few feet of film run through the apparatus.

On taking a length of film which has passed the erasing head and moving it by hand slowly backwards and forwards past the reproducing head, you can hear a clearly audible note from the film. This, when listened to carefully, and—more particularly—if analysed on an oscilloscope, proves to originate from the supersonic erasing or bias frequency which has been moved into the audible range by the decrease in the reproducing speed.

From this experiment it is thus clear that after the magnetic film has been treated with the supersonic erasing or bias current, as just demonstrated, it does not leave the wiping head in a completely demagnetized state—as has previously been thought the case—but with the supersonic frequency recorded on it. The amplitude of this supersonic frequency is, of course, very small, due to several factors of which the most important is possibly the increased demagnetization factor at such a high frequency.

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Using an erasing head with a gap width of 0·008 in., it is possible to record a 50,000-c/s note on the film. This shows that the gap width does not determine the highest frequency which can be recorded.

The limit to the highest frequency which can be recorded is, apparently, largely decided by the rapidity with which the magnetic field decreases on the side where the film leaves the gap.

In the construction and operation of an erasing head to operate at the optimum efficiency it must, therefore, be the aim to make this decrease of the magnetic field take place as slowly as possible. This can be done to a certain extent by increasing the amplitude of the supersonic erasing current, thereby extending the area near the gap over which the strength of the magnetic field diminishes.

It has been found that, by increasing the amplitude, the actual amount of the 50,000 c/s note recorded in the manner just described will gradually diminish since the act of increasing the amplitude is equivalent to spreading the magnetic field. Even so, it has not been found possible to obtain a complete wipe or demagnetization of the film by this method as even with the largest amplitude, which it has been possible to employ practically, there has still been some trace of the 50,000-c/s note remaining on the film which seems reasonably conclusive evidence that, in fact, the film does not leave the erasing head in a completely demagnetized state.

As a point of interest, we would mention that, in the experiments which we have made in our laboratories, we incorporated an additional motor in the apparatus, geared to a speed ten times slower than that of the standard recording speed, so that, after a recording of the 50,000-c/s note had been made at the normal film speed, it was possible to play it back at a tenth of this speed. In this way we were able to hear a 5,000-c/s note and also to reproduce it visibly on an oscilloscope.

13. Comparison between A.C. Mains and Supersonic Wiping

Actual measurements taken during an experiment to determine the reduction of the recorded signal by erasing are shown in Fig. 8, which shows the effect of the wiping head on the full line curve A and, on the adjacent perforated line curve B, the additional assistance in erasing given to the wiping head by the recording head. The curve A goes down as far as the —70 db level, whereafter no further erasing action can be made. In contrast to this the horizontal line C, drawn at approximately the —80 db level, shows the amount of attenuation reached immediately when a reel of recorded film is wiped in an a.c. mains-energized wiping apparatus.

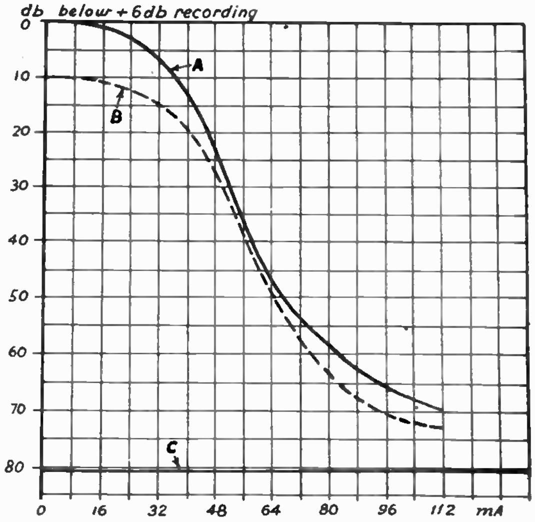

Fig. 8.—Comparison between a.c. mains and supersonic wiping

It can be concluded from the curves illustrated that wiping with a supersonic frequency is not quite so efficient as with the a.c. mains-energized apparatus, but the limit of —70 db is, nevertheless, very satisfactory for all practical purposes, especially bearing in mind that, when recording with a H.F. bias, it is not always possible to obtain a higher ratio between the levels of the actual background noise and the signal actually obtained.

14. Low-Speed Wiping

Some investigations have been made in our laboratories regarding the possibility of erasing recorded magnetic signals by means of a H.F. erasing current which is applied to the film, via a suitable wiping head, whilst the film is run at a speed approximately one-tenth of the normal recording speed. At this low wiping speed, which is roughly 2 in/sec, we had expected to obtain a better erasure of the recorded signals, but, in fact, no such result was achieved. This will be seen from Fig. 9, which illustrates in the full-

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lined curve the amount of attenuation obtained by wiping a recorded film at the normal film speed but at different values of wiping current, the maximum attenuation achieved being as much as approximately −65 db and, in the perforated-lined curve, the amount of attenuation achieved by wiping a further part of the same recorded film at a speed only one-tenth of the recording speed. It will be observed that the perforated-lined curve very nearly coincides with the full-lined curve and that hardly any better results were obtained.

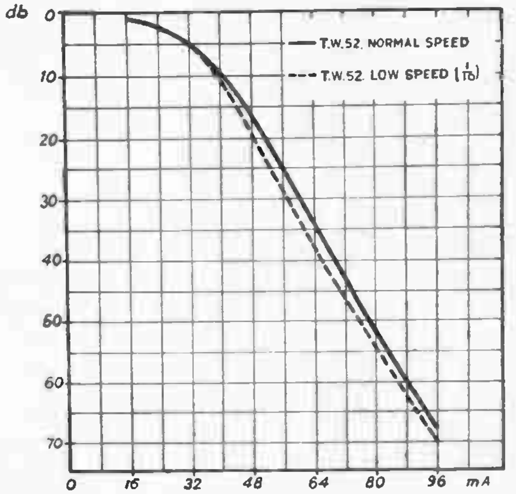

Fig. 9—Relative efficiencies of normal and low-speed wiping.

15. Conclusion

One of the principal conclusions to which we come, therefore, as a result of the experiments referred to, is the fact that it is perfectly feasible to record very high frequencies on a magnetic film running at the normal film speed of 18 in/sec. This will, perhaps, be some encouragement to research workers to devise methods and apparatus whereby ultrasonic frequencies can be recorded, thereby opening the door to the possibility of recording pictures as, for example, for television purposes, simultaneously with a complementary sound record. This possibility has, in fact, already been advanced by scientists in several countries.

16. Acknowledgments

I should like to express my thanks to Col. Elliott for his assistance in preparing the figures and to Mr. Petersen for the investigations and data which he has supplied for incorporation in this paper.

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A NEW APPROACH IN THE DESIGN OF EQUALIZED FILTERS AND DELAY LINES*

by

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SUMMARY

The phase characteristics of filter networks and delay lines can be equalized by bridging mutual inductance sections capacitatively. The solution of the resulting nth order equations is difficult. An approach which considers the transient response yields a simple solution. This study was completed in 1946.[6,7]

It has long been the aim of research workers to improve the phase characteristic of filter networks and delay lines. A transmission delay varying with frequency corresponds to a non-linear phase characteristic. This means that all frequencies transmitted through the system travel with different velocities and arrive at different times. This results in a distortion of the transmitted signal. Although there is a relationship between the phase and attenuation characteristics of a network, in many applications it is desirable to obtain a linear phase characteristic even if obtained by affecting the attenuation characteristic. For instance, in the transmission of frequency modulated signals through radio links, a non-linear phase characteristic results in a distortion of the signal transmitted while amplitude variations can be eliminated by proper limiters. A linear phase characteristic is also desirable in the transmission of signals through delay lines. As long as the number of sections used is not great, the phase distortion is small and the line can be used up to frequencies very near the nominal cut-off. When, however, the number of sections increases, the phase distortion is no longer negligible. Signals applied simultaneously to the delay line, and of different oscillating frequencies, arrive at the far end successively with delays increasing with the number of sections. The greater the number of sections, the smaller the portion of the pass-band transmitting all frequencies with constant velocity.

Initially delay lines were composed of equal series inductances and shunt capacitances. This arrangement offered a good flat amplitude characteristic up to the cut-off frequency but poor phase characteristic. A notable improvement in the phase characteristic was contributed by Professor G. W. Pierce[1] as early as 1921. He discovered that a certain amount of mutual inductance between adjacent sections is beneficial. This yields a simple construction, particularly if a continuous winding with convenient tappings is used.[2] Later the author produced linear phase-shift filters, by proper reflections produced in the successive sections of a line mounted in a bridge circuit.[3] This filter has, however, the disadvantage of an appreciable transmission loss in the pass-band. More recently Pierce's idea was extended by considering the influence of mutual inductance between alternate and more distant sections,[5] and also the influence of capacity bridging. Simultaneous studies were done by Golay in America,[4] and the author in England.[6,7] These were followed later by other studies, amongst which was an interesting investigation by Professor L. Brillouin.[8] These studies are based on a method used previously by Professor L. Brillouin.[3]

Consider a recurrent assembly of series inductances with mutual inductances, $\alpha_1 L$, $\alpha_2 L$, $\alpha_3 L$, etc., between adjacent, alternate and more distant sections, and capacitances C to ground. Kirchoff equations for the nth section yields:—

$$2(1 - \cos \varphi) = \omega^2 LC \, [1 - 2\alpha_1 \cos \varphi - 2\alpha_2 \cos 2\varphi \ldots\ldots\ldots]$$

The requirement of no attenuation below cut-off and no phase distortion may be expressed by the condition that the phase φ be real and proportional to the angular velocity ω

$$k\varphi^2 = \omega^2 LC$$

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which in combination with the above expression yields:

$$\frac{2(1-\cos\varphi)}{k\varphi^2} = 1 - 2\alpha_1\cos\varphi - 2\alpha_2\cos 2\varphi\ldots\ldots$$

This equation will be satisfied between the limits $\varphi = 0$ and $\varphi = \pi$ if the second member is considered as the Fourier expansion of the first member between said limits. This yields particular values for the coefficients α_1, α_2..... It is found that the successive odd order mutual inductances should be additive, while the successive even order mutual inductances should be subtractive. This obviously cannot be realized simply. Fortunately capacitance bridging can, so to speak, neutralize the mutual inductance and even operate as a subtractive mutual inductance. Simultaneous mutual and capacitance coupling yields a complicated equation, to which Brillouin and Golay give different approximate solutions. By a different method Ferguson[9] obtains another approximate solution.

It appeared to the writer that approximate solutions of an iterative equation cannot be satisfactory unless the errors are extremely small. The reason is that if an error of 1 per cent. is made on the delay per section, the error is *n* per cent. for *n* sections, that is, it increases with the number of sections. Although the above solutions yield a linear phase characteristic for one section with reasonable accuracy, the errors are additive and the phase distortion for *n* sections becomes appreciable when *n* is greater than, say, 10.

For this reason an attempt was made to solve the problem by considering the phase characteristic of *n* simultaneous sections. Mathematically this yields an equation of the nth order which seems very difficult to solve. Fortunately the transient approach mentioned in an earlier paper[2] yields a simple solution. Consider the pulse response of an ideal delay line (Fig. 1*a*). It is represented by a curve of the type sin x/x, that is with an even symmetry. It has been shown[2] that the phase shift is linear if the pulse response presents an even symmetry. Consider now the pulse response of a delay line with a certain amount of mutual inductance between adjacent sections (Fig. 1*b*). This curve is not symmetrical. In the absence of mutual inductance the dissymmetry is still more appreciable. In particular the response starts as shown by the dotted line. If we compare this response with the ideal response, we note that by adding the odd symmetrical oscillations shown on (*c*), we obtain a curve similar in appearance to the ideal curve. In an approximate way this can be obtained by the following process illustrated on Fig. 2. Take the derivative (*b*) of the transient response (*a*). In a first approximation we can neglect the secondary oscillations and limit the curve to one main oscillation presenting an odd symmetry with respect to time $t = \tau$, where τ is the delay of the line as defined in (*a*), Fig. 2, or in Fig. 1. Now assume the oscillations of the tail of the transient response to occur with a period τ_0. If we shift the derivative by $-\tau_0$ and $+\tau_0$, $-2\tau_0$ and $+2\tau_0$, etc., after proper attenuation we get the successive curves shown in (*c*). The resultant of these elementary curves is shown in (*d*) and is very similar to the odd symmetrical curve shown in

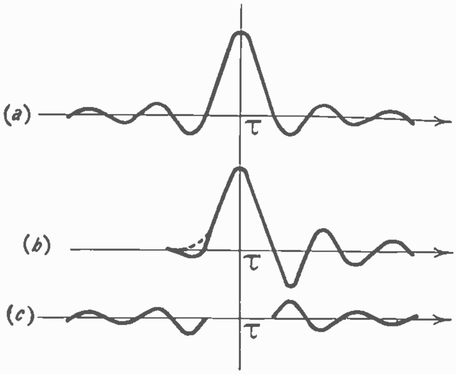


Fig. 1.—Pulse responses of delay lines.

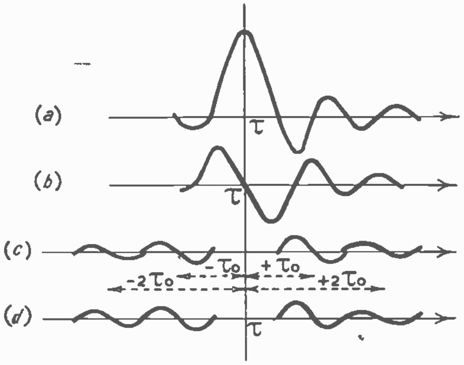


Fig. 2.—Pulse response (a), derivative (b), and combination of derivatives, (c) and (d).

(*c*), Fig. 1. Adding this curve to the transient response (*b*), Fig. 1, we get a symmetrical transient.

In practice, these operations can be performed very simply by means of bridging capacitances as shown in Fig. 3. Consider a delay line terminated by its characteristic impedance and supply a short pulse at the input. Normally the pulse will travel through the line with a certain speed and will be absorbed when it reaches the end of the line. If, however, a capacitance is bridging points A and B, distant by a delay τ_0, when the pulse arrives at A, the derivative of the pulse (which has been distorted and looks more or less as the transient response of the line) appears at B. The transient pulse comes at B after a time τ_0. At this moment a derivative appears at A and travels towards B with a delay τ_0. A derivative is obtained only if the characteristic impedance of the line is small compared to the impedance of the bridging capacitance. Usually this capacitance need only be a small fraction of the shunt capacitance so that this condition is satisfied. Fig. 3 shows in (*b*) the resultant signal as it appears after points A and B, in (*c*) a delay line with three bridging elements and in (*d*) the resultant transient response.

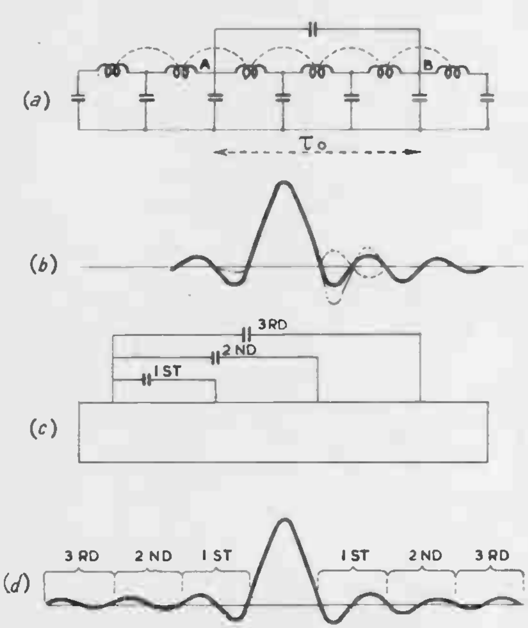
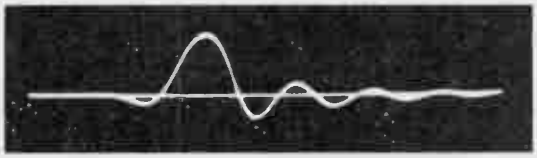


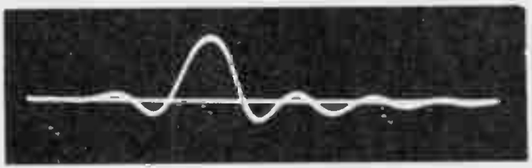
Fig. 3.—*Bridged delay lines and responses.*

From the practical point of view it is essential that the bridging points such as A and B (Fig. 3) should be section points. This means that the period of the secondary oscillations should be equal to the delay produced by an integral number of sections. It can be shown both theoretically and experimentally that this is most simply achieved by using a delay line with about 12 per cent. mutual inductance between adjacent sections. In this case the period of the secondary oscillations is very nearly equal to the delay produced by these sections and bridging is done every three sections or multiple of three sections.

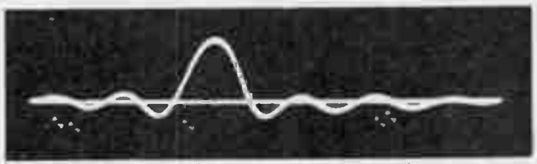
It is a remarkable fact that in practice this process can be carried out easily. Usually the pulse response is corrected reasonably by three bridging capacitances of very small value. Alternatively, each capacitance can be replaced by *n* capacitances bridging a similar number of sections and of smaller value. Fig 4 shows a practical result and Fig. 5 the phase-response of this type of filter.



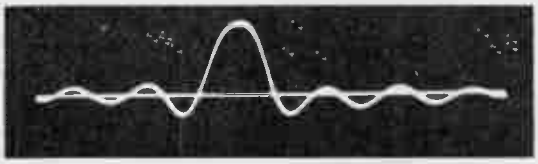
(*a*) Response of a delay line with 12 per cent. mutual inductance



(*b*) Same line with one capacitative coupling.



(*c*) Same line with two capacitative couplings.



(*d*) Same line with three capacitative couplings.

Fig. 4.—*Oscillograms of responses of delay line.*

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It may be mentioned that the process indicated above does not agree with the theoretical values given by Golay. In fact a delay line designed with the construction values approximately equal to those indicated by Golay (mutual of about 18 per cent., bridging across every two sections and multiples of two sections) did not give a symmetrical pulse response. It has been explained already why the classical approach does not give a satisfactory answer unless very great care is taken.

The new approach sketched above is based on theoretical considerations very obvious to those familiar with the notion of "selective transforms."[10] It can be shown that the transformation of Fig. 1, that is, adding curve (*c*) to curve (*b*) to obtain the symmetrical response (*a*), results, in the first approximation, in correcting the phase characteristic of (*b*) without affecting appreciably its amplitude response. This is due to the fact that (*c*) presents an odd symmetry and its frequency components are at right angles to the corresponding frequency components of (*b*) so that the addition of these two curves results substantially in a phase shift only. A detailed theoretical study predicts the phase correction shown in Fig. 5, and explains why a crossing point C exists and why a phase reversal occurs through this point.[11]

The above considerations are very elementary in that they neglect many factors of importance in practical design. These can only be fully explained in a detailed study. A complete account will appear in a subsequent paper.

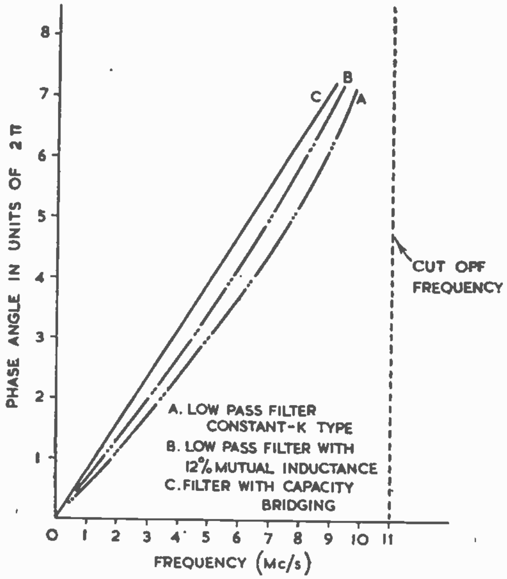

Fig. 5.—Phase response of filters.

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