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RADIO-FREQUENCY STANDARDS

THE growth of mechanical and electrical engineering in the last one hundred years was accompanied by a realization of the need for national standards for the primary units involved. This need was eventually met and we now have in the National Physical Laboratory an organization of international repute and stature, which in questions regarding the absolute magnitudes of the primary electrical and mechanical parameters, is the accepted arbiter. However, the expansion of radio and electronic engineering has been so rapid in its applications, in the frequency spectrum used and in the precision demanded, that a centralized and comprehensive national laboratory for the standardization of all the measurement techniques involved has not yet emerged.

The last two decades have seen an extension of the usable frequency spectrum to at least 40 000 Mc/s with a corresponding demand for an increasing refinement of the techniques of measuring fundamental parameters. Except in respect of frequency, techniques have not been developed in the unified manner required to ensure such authoritative standards of accuracy as are essential to disciplined progress in a scientific and engineering field.

Through sheer necessity individual organizations have had to develop their own techniques, inevitably with limited objectives in view, and there has been no co-ordination or general availability of the results. That this situation presents a serious problem is well known to radio engineers, especially those intimately concerned with the higher frequencies. The dispersal of effort is uneconomical as well as being ineffective; time is wasted in arguments as to the validity of measurements carried out in isolation without national standards of reference.

The first essential of standardization is a central authority. In the National Physical Laboratory we have an organization of the precise character required to pursue this important and pressing task. It has well upheld our national prestige throughout its 60 years as a "Public Institution for standardizing and verifying instruments, for testing materials, and for the determination of physical constants".

It may not be fully appreciated that N.P.L. is not covering with full effect the standardization needs of the radio engineer outlined here. That this is the case, undoubtedly due to inadequate financial and organizational support, is shown by a study of the Laboratory's published schedules of standardization services. With a few exceptions measurement facilities are not available at frequencies higher than 5 Mc/s. The main exceptions are the measurement of propagation constants of radio-frequency cables, of permittivity and power factor of insulating materials, and of power factor of capacitors; the last two cases only involve numerically specified extensions to 100 and 150 Mc/s respectively. Some additional unscheduled facilities do exist but the total coverage falls far short of current needs.

International discussions of standardization problems had some prominence in the 13th General Assembly of U.R.S.I. held in London last September. On this account alone it is timely to reflect on the need for consolidating facilities, not only to support the insular needs of our profession and industry but also to participate effectively in the international co-operation demanded by the global and, shortly perhaps, spatial nature of our activities.

The National Physical Laboratory was one of the first of its kind to be founded at the beginning of the century. It is hoped that the Laboratory will maintain its pioneer work by extending its facilities for radio-frequency standardization, or in helping to establish a special organization for this purpose. It is an essential service to help the radio engineer to cope with the ever-growing international complexity of science and technology.

F. G. D.

INSTITUTION NOTICES

Inaugural Meeting of the Television Group

Reference was made in the January *Journal* to the work which the Television Group Committee has undertaken for the Council in preparing evidence for the Government Committee on Broadcasting. In addition the Committee has made arrangements for three Group meetings during the current Session. Details have been announced in the "Programme of Meetings" dispatched to all members last month.

The first of these is the Inaugural Meeting of the Group on Wednesday, 1st March when an address will be given by Mr. Leslie H. Bedford, C.B.E., M.A., B.Sc.(Eng.), F.C.G.I., a Past President of the Institution. As members will know, both before the war and immediately after, Mr. Bedford was closely concerned with the design of both transmitting and receiving equipment for television broadcasting; in 1954 his paper on "Problems of Television Cameras and Camera Tubes" (published in the *Journal* for October 1954) was awarded the Sir Louis Sterling Premium. It is certain that many members not concerned professionally with television will want to hear his address.

The meeting will be held at the London School of Hygiene and Tropical Medicine, and will start at 6 p.m. (please note time alteration).

D.S.I.R. Inquiry into the Use of Film in Scientific Research

The Department of Scientific and Industrial Research has set up a working party, under the chairmanship of Dr. W. L. Francis, to consider national needs in the field of scientific film. The working party is especially interested in the aspects of film as a research tool and in communicating research results.

D.S.I.R., in co-operation with Research Councils, the Atomic Energy Authority and some Government Departments, is circulating a questionnaire to industry, universities and research organizations. In this way it is hoped to reach all those engaged in the serious use of film in this field who hold stocks of interesting research film or who have developed unusual techniques and applications.

Any member of the Institution who can contribute to this inquiry, but who has not received the questionnaire, is invited to approach the Information Division of D.S.I.R., 14 Cornwall Terrace, London, N.W.1.

Back Copies of the *Journal*

A very prompt and large response was made by members in returning back copies of *Journals* asked for in the January issue. A large enough number was received to fulfil existing orders and provide a stock for the future. Will members therefore please note that *no further copies of these issues are required.*

Electronic Instrumentation for Cardiac Surgery

The Medical and Biological Electronics Group of the Institution, and the Post Graduate Medical School of the University of London, are combining to arrange a symposium on "Electronic Instrumentation for Cardiac Surgery". These meetings will be held in the Lecture Theatre of the Post Graduate Medical School, Ducane Road, London, W.12, on Monday, 27th March, commencing at 2.30 p.m.

Papers will be presented by surgeons and electronic engineers under the following headings:—

1. Pressure Measurement.
2. Flow Measurement.
3. Automatic Biochemical Measurement.
4. Instrumentation in the Operating Theatre:
   (i) Amplification of Biological Signals.
   (ii) Display of Monitored Results.
5. Defibrillation and Pacemakers.

The chairman of the symposium will be Dr. D. G. Melrose, B.M., B.Ch., Department of Experimental Surgery, Post Graduate Medical School, University of London.

Contributors include:—

J. P. Shillingford, M.D., F.R.C.P.
W. J. Perkins, M.Brit.I.R.E.
H. H. Bentall, F.R.C.S.
L. D. Abrams, F.R.C.S.
C. K. Battye, B.Sc.
C. A. F. Joslin, M.B., B.S., A.M.Brit.I.R.E.

Tickets may be obtained from the Secretary of the Medical and Biological Electronics Group, 9 Bedford Square, London W.C.1, or from the Secretary, Experimental Surgery Department, Post Graduate Medical School, Ducane Road, London, W.12.

Change of Address—an Urgent Request

All members are earnestly requested not to delay in advising the Institution at 9 Bedford Square, London, W.C.1, immediately they change their address.

It is *not* necessary for members to notify local section secretaries in Great Britain of their change of address. Such notifications are automatically sent from Head Office to the local sections. Because of delays in post, however, overseas members should advise their Local Secretary *at the same time* as they advise the London Office.

Failure to notify the Secretary at 9 Bedford Square causes considerable delay in members receiving *Journals*, notices of meetings and other separate communications. In addition there are extra postal charges involved due to letters being returned to the Institution. For all these reasons it is hoped that members will co-operate in the manner requested.

U.D.C. 621.37/9.002.3

The Application of Modern Materials to Electronic Components

Presented at the Symposium on New Components, held in London on 26th–27th October 1960.

By

J. M. HERBERT, B.Sc.†

AND

R. G. MARTIN†

Summary: New developments in component materials and techniques are discussed under the following headings: capacitors (ceramic disc, barrier layer and tantalum electrolytic); piezoelectric devices (filters); inductive devices (core, parametric and transformer techniques); semiconductors (tunnel diode, variable capacitance diode, silicon controlled rectifier, thermo-electric components, solar cell, Hall effect); information storage systems (square loop ferrites); microminiature devices (component substrate, vacuum deposition, solid circuits). Transistors and thermionic tubes are not considered.

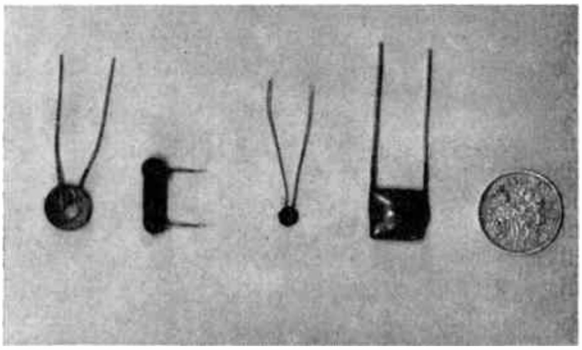
1. Introduction

This paper is not intended to be an exhaustive survey of the present status of materials and components. It is a selection based on the authors' experience which, it is hoped, will cover a sufficiently wide field to be of general interest. In considering new components, division into commercial, military or professional classes cannot usually be made because in their early stages most new components are too expensive for the commercial radio market. Widespread use must wait for the development of mass production manufacturing equipment and a high degree of standardization. Only certain recently developed materials and techniques are considered here and developments in thermionic tubes and transistors have been excluded.

2. Capacitors

Miniature disc and tubular units (Fig. 1) which make use of the high dielectric constant obtainable with barium titanate ceramics have been in use for several years now. The values of these units lie between 500 and 10 000 pF. The trend towards lower voltages occasioned by the use of transistors has led to further miniaturization by allowing the use of thinner dielectrics. The range of values can be increased by firing several layers of dielectric together to form a multi-plate capacitor. So far this technique has necessitated the use of palladium for the electrodes and such units are therefore expensive. Some economy can be achieved by making use of the very high permittivity obtainable near the Curie point, but this results in considerable temperature and voltage sensitivity (Fig. 2). However, 1 μF 50 V units can be made in a size ¾ in. × ½ in. × ⅛ in., which is comparable in size with transistors, so that when cheaper electrodes can be used, a useful component will be available.

Another approach to the miniature capacitor problem is the barrier layer dielectric.[1] Barium titanate is first prepared in a highly conductive form by firing a suitable composition in a reducing atmosphere. Careful oxidation of the surfaces under the usual type of fired on silver electrodes then causes the formation of thin barrier layers which can have capacitances of about 1 μF/cm^2 (Fig. 3). The resulting



(i) 2000 pF 300V disc. (ii) 2000 pF 300V tubular. (iii) 2000 pF 100V thin plate. (iv) 1 μF 50V film pack. (v) Sixpenny piece.

Fig. 1. High permittivity capacitors.

component has the current voltage characteristic of two rectifiers connected back to back (Fig. 4). The resistance-capacitance product falls off rapidly with applied voltage (Fig. 5) and is never greater than 3 sec for the particular unit examined here. This may be contrasted with 500 to 1000 sec for the multi-plate high permittivity unit described previously. Although the resistance falls with increasing temperature the drop in resistance-capacitance product is not excessive.

† The Plessey Co. Ltd., Towcester, Northants.

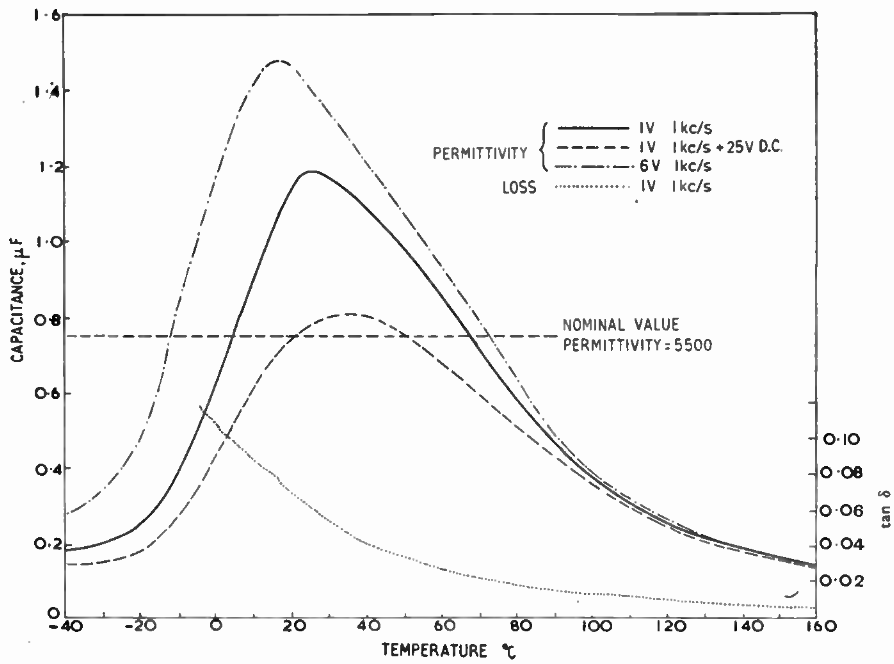


Fig. 2. Palladium electrode film pack (American source)—Temperature characteristics.

The power factor is of the order of 2% at low voltages (Fig. 6). The capacitance value varies somewhat with voltage but is not particularly sensitive to temperature (Fig. 7). The voltage rating of this type of unit can be increased at the expense of the capacitance value. They are being used extensively in America in such applications as hearing aids.

The advantages of the sintered anode tantalum electrolytic capacitor over other types in terms of small size, stability, low leakage current and the ability to function at high temperatures are well known. The range of sizes is being constantly extended but the difficulties of sealing the smaller types will be readily appreciated when it is realized that the seal must be proof against hot pressurized sulphuric acid. For this reason much work has been done to develop capacitors with no free electrolyte, and these will soon be produced in this country. The maximum voltage is of the order of 35 V and power factors of better than 5% may be obtained (Fig. 8). They should have wide application in professional and industrial transistorized circuits. A comparison of similarly rated electrolytic capacitors showing the reduction in size over the years is of interest (Fig. 9).

3. Piezoelectric Devices

Suitable grades of barium titanate continue to be widely used in piezoelectric applications, and a considerable advance has been made by the development

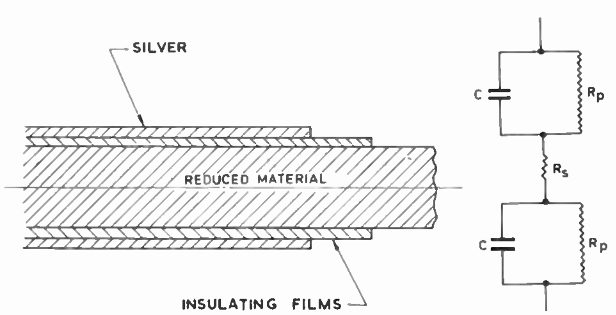


Fig. 3. Barrier layer capacitor—diagrammatic representation.

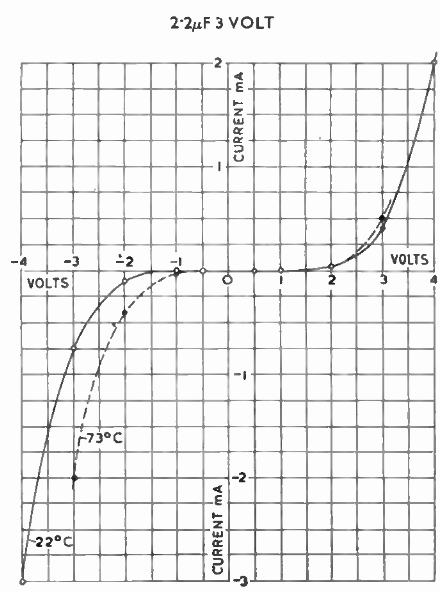


Fig. 4. Barrier layer capacitor—current/voltage characteristic.

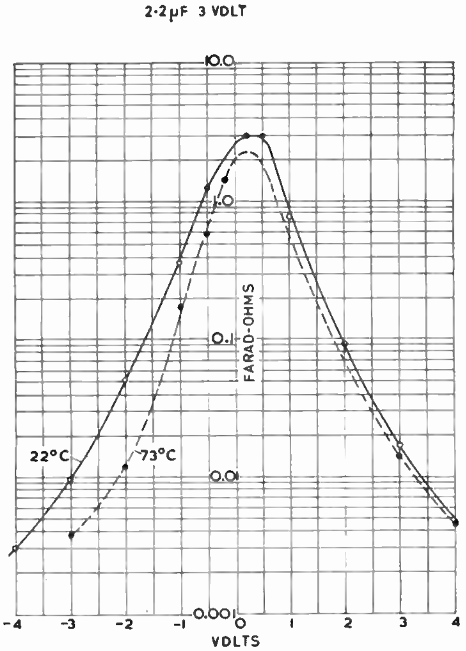


Fig. 5. Barrier layer capacitor—resistance capacitance product/voltage characteristic.

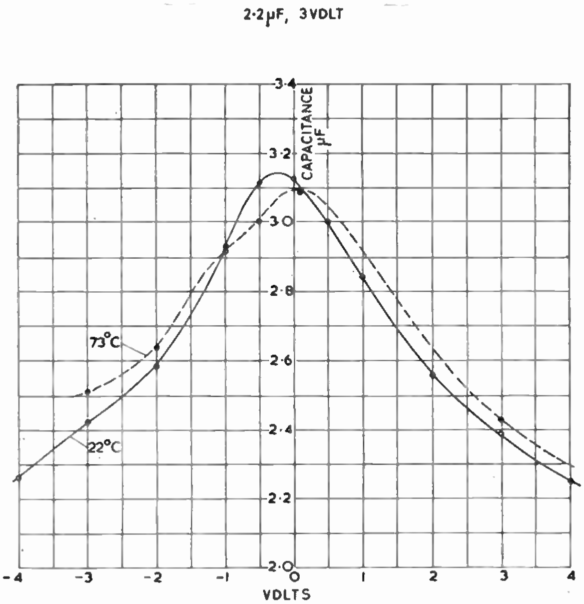


Fig. 7. Barrier layer capacitor—capacitance as a function of voltage and temperature.

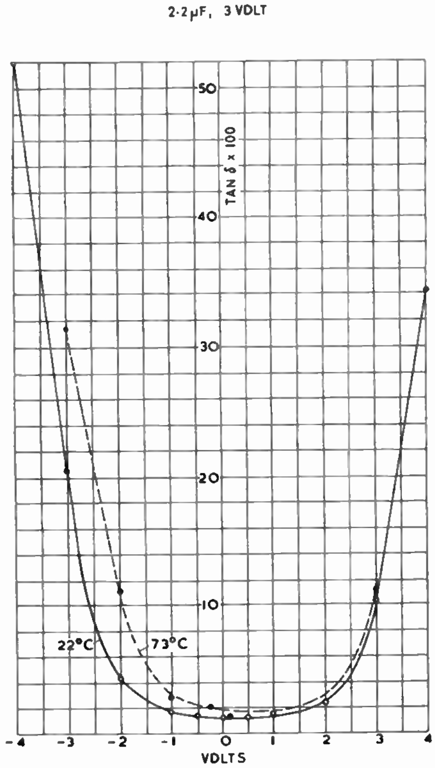


Fig. 6. Barrier layer capacitor—loss/voltage characteristic.

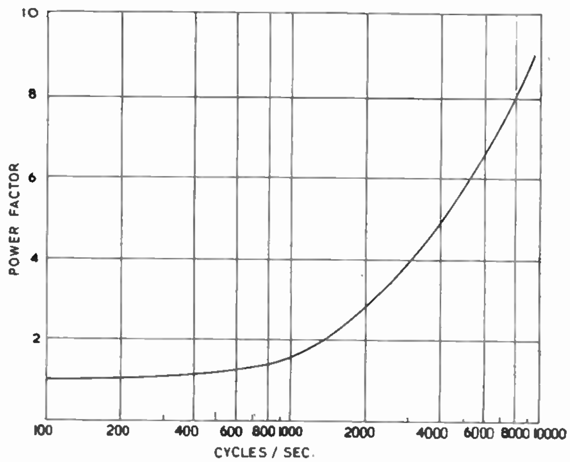


Fig. 8. Dry tantalum capacitor—frequency/power factor characteristic at 25°C.

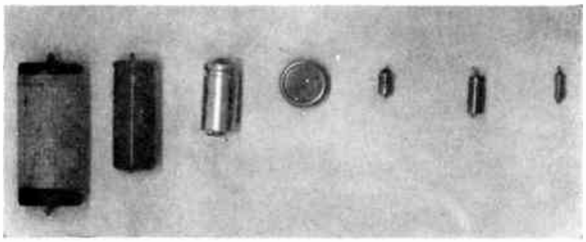


Fig. 9. Various electrolytic capacitors showing size relation.

of lead titanate-zirconate ceramics—largely in the U.S.A.[2] Not only has this led to materials with higher piezoelectric coefficients but also to materials with properties which are more stable with respect to both time and temperature. These bodies are appreciably more difficult to make than those based on barium titanate, partly because of the volatilization of lead oxide during the sintering process and partly because their final properties are remarkably sensitive to the details of the manufacturing procedure. Their higher activity make these materials attractive for pick-up cartridges, ultrasonic generation and underwater signalling. Their stability has led to proposals to use them in filters. An interesting possibility is a three-terminal device developed in different forms in the U.S.A.[3] (Fig. 10) and in this country.[4] The unit

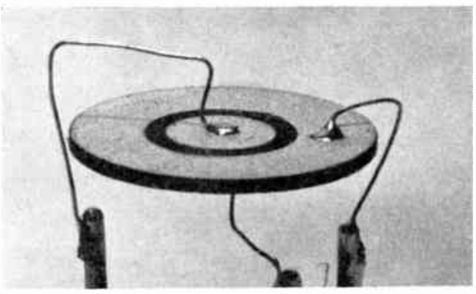


Fig. 10. Three-terminal piezoelectric filter disc.

consists of a ceramic disc silvered completely on one side and with the centre and periphery silvered separately on the other. The completely silvered surface forms a common terminal. An input to one part of the other surface causes the disc to vibrate mechanically and thus to give an electrical output from the other part. Energy is only transferred efficiently when the frequency corresponds to that of a mechanical resonance of the disc and this device therefore acts as a filter. The use of such a component in i.f. strips is complicated by two features, firstly the need to provide a d.c. path between the associated transistors and secondly the elimination of unwanted harmonics. The first simply causes some loss of efficiency while the second can be achieved by having some units working at their fundamental frequency and others, of larger diameters, working at their second harmonic. As the input and output impedances of these discs are inversely proportional to the silvered areas, matching to the input and output circuits can be obtained. At the moment, units of this type are expensive: a disc with its fundamental radial resonance at 500 kc/s is only $\frac{3}{16}$ in. in diameter so that it is not a simple matter to control the dimensions sufficiently accurately to give the required frequency within a close tolerance.

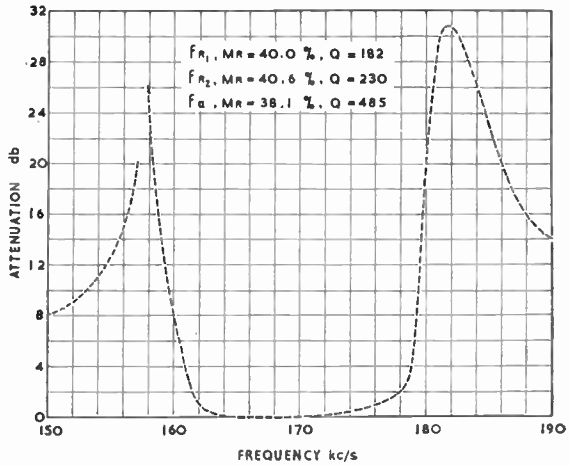


Fig. 11. Impedance/frequency characteristic of three disc lead titanate-zirconate piezoelectric filter.

Assemblies of discs forming complex filter networks can be designed to give a wide range of useful characteristics (Fig. 11).[5] Implementation of these designs depends on the development of adequate methods for manufacturing to close frequency tolerances and on the establishment of compositions which combine the necessary mechanical Q and electromechanical coupling coefficient with the necessary order of stability.

An ingenious electromechanical filter is being produced in Japan[6] (Fig. 12). The main control of the frequency is due to two ball bearings vibrating in a spheroidal mode. Barium titanate transducers are used to convert the electrical input to mechanical vibrations and vice versa. Impedance matching is

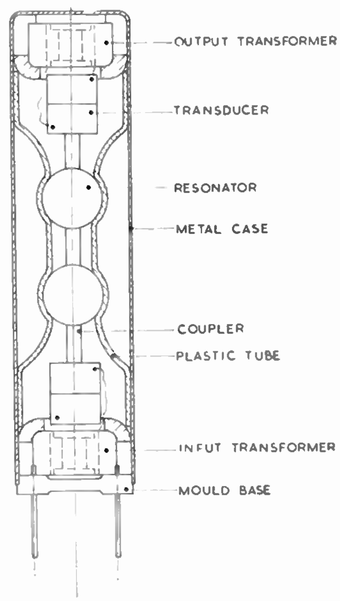


Fig. 12. Electromechanical filter using ball bearings.

obtained with small transformers. Typical characteristics are shown in Fig. 13. The device is relatively complex but neatly solves the problem of grinding to frequency by using ball bearings for which a precise technique is well established.

A ferrite has been developed[7] which may also serve as a stable filter element. The temperature at which

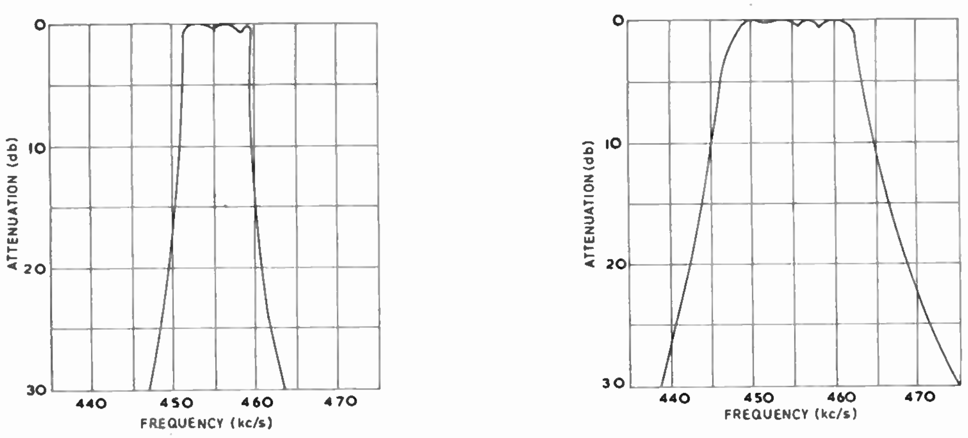


Fig. 13. Electromechanical filter using ball bearings—attenuation characteristics.

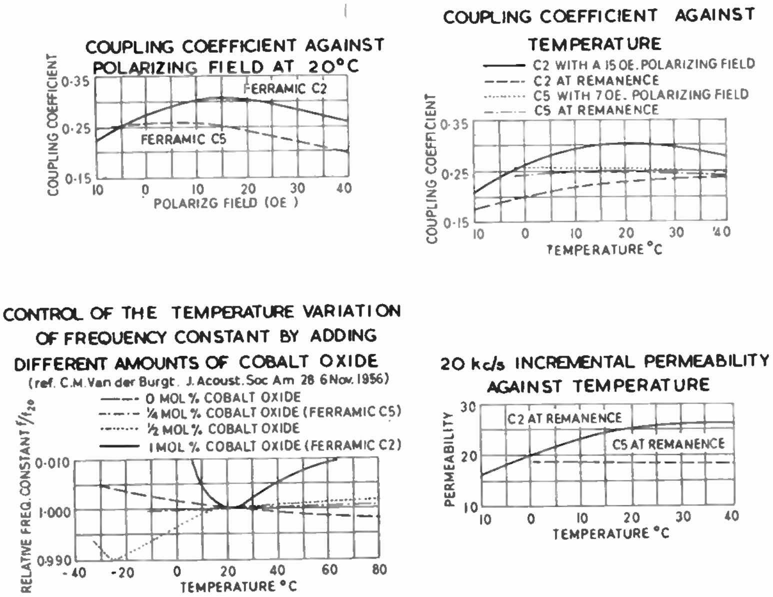


Fig. 14. Magnetostrictive ferrites—temperature characteristics.

the anisotropy coefficient of nickel ferrite is a minimum can be adjusted accurately by substituting a small amount of cobalt for nickel (Fig. 14). As a result the frequency constant for magnetostrictive vibration is very little affected by temperature and the initial permeability is also remarkably constant. The material has a coupling coefficient (in toroids) of 0·25 with a mechanical Q of about 600. Higher mechanical Q values can be combined with lower coupling coefficients. It may thus serve for narrower bandwidth applications than lead titanate zirconate.

4. Inductive Devices

An important advance in ferrite technology is making it possible to produce core materials which are closely reproducible and stable with respect to both temperature and time. In composition they are the familiar manganese-zinc ferrites, but the raw materials are selected for purity and the composition is carefully controlled; for example, allowance is made for any iron introduced during milling operations. The atmosphere during firing and the temperature-time schedule are also precisely controlled, the main feature being the partial or complete exclusion of oxygen during a part of the cycle. Such cores can be used for the inductors in filter networks in such applications as multi-channel telecommunication systems (Fig. 15) and result in considerable economy in space.[8, 9]

Many devices have been produced using ferrites at microwave frequencies and there has recently been some interest in single crystals of yttrium iron garnet as a material for a parametric amplifier. Little use has been found for ferrites in the range 10 to 500 Mc/s, largely because existing materials are lossy and of low permeability at these frequencies. Some remarkable materials have been developed, notably the Ferroxplanar series, which have permeabilities of 10 or above in this range and with Qs above unity up to 1000 Mc/s,[10] but very little use has been made of them as yet. On the practical side a 50 Mc/s attenuator has been based[11] (Fig. 16) on a conventional nickel zinc body in the form of a transformer core. The core lies in the gap of an electromagnet so that its permeability can be varied between unity and some higher value by varying the current in the magnet winding. The coupling between the windings on the core can thus be varied. The relationship between input and output voltages for a particular circuit using this device is shown in Fig. 17. This device has the advantages that it does not affect the noise factor or the maximum power dissipation in

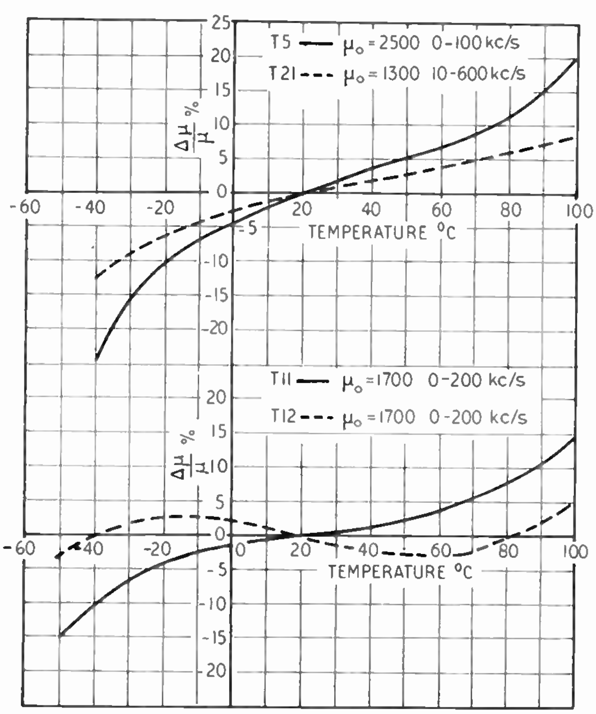


Fig. 15. Initial permeability/temperature relations for telecommunication pot core ferrites.

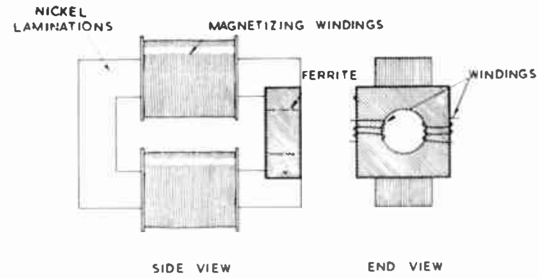


Fig. 16. Variable coupling transformer.

associated circuits and does not cause any changes in centre frequency or bandwidth. It permits automatic gain control without the limitation of input signal necessary with devices using transistors.

5. Semi-conductor Devices

The design of power supply equipment is making rapid progress due to the introduction of semi-conductor devices. In the domestic radio and television markets increasing use is being made of silicon junction rectifiers. These are much smaller than either selenium or thermionic valve types, require no heaters, drop less than one volt in the forward direction at full rated current and possess a back-to-front ratio of better than 10^6. Unfortunately, they cannot tolerate large current overloads, but this is not proving a great disadvantage with suitable circuit design.

The negative resistance characteristic (Fig. 18) of tunnel diodes[12] is being actively exploited and oscillators, amplifiers and storage devices capable of operating at very high frequencies are being developed. Much work appears to be necessary before their use becomes widespread.

The variation of capacitance of a diode when electrically polarized in the reverse current direction is being used as a variable tuning element in radio equipment.[13] A number of specialized variable capacitance diodes are now available and the use of this technique in automatic frequency control circuits can be expected to increase.

Many mobile radio equipments have rotary generators or vibrators incorporated in their power supply systems. These are often heavy, noisy and troublesome in use, but newly developed semi-conductor devices are providing a useful alternative. A direct-current source can be used to power a semi-conductor oscillator operating at a convenient frequency whose output can be transformed to a suitable voltage and used to drive equipment direct or through silicon rectifiers. This is a field of development which is being actively pursued and units of considerable power are now possible with the introduction of the three-terminal controlled rectifier which has a function similar to the thyratron. Suitable feedback circuits

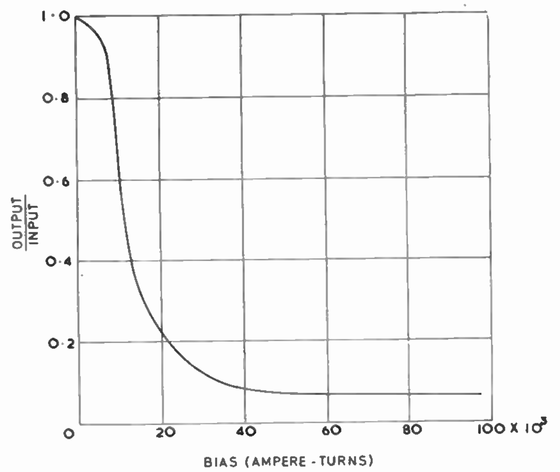


Fig. 17. Output/input voltage characteristics of circuits coupled by variable coupling transformer.

can be used to provide a controlled output in terms of either voltage or current.

Mention may also be made of the range of devices made possible by the use of thermoelectric materials. The Seebeck effect is well known, but apart from its use in thermocouples for temperature measurement and, pre-war, for a gas-operated battery eliminator, it has not given rise to devices of much practical significance. For the last few years increasing attention has been paid to a number of inter-metallic compounds such as bismuth telluride and lead selenide which offer the prospect of a high conversion efficiency.[14] In several countries work is in hand to produce electrical power directly from a heat source and already units capable of supplying some kilowatts of energy are available with efficiencies of about 7%. An ultimate efficiency of about three times this figure is thought to be feasible.[15] This should have considerable influence on the power supplies for mobile radio equipments, particularly in aircraft where convertors may be operated from heat exchangers connected to the exhaust system of the aircraft engines.

Another technique for obtaining electrical energy is direct conversion from sunlight by a device usually known as a solar cell. It is already used for powering satellites, remotely sited communications equipment and even hearing aids. The basis of the device is a diffused junction about 0·0001 in. below the surface of a silicon wafer wherein the incident solar radiation is converted to electrical energy. Some 100 watts of power per square metre of surface can be generated with a voltage of about 0·4 per cell and with a conversion efficiency of about 10%. The wafers are usually of the order of 5–10 cm², and by suitable series/parallel connection convenient voltages and currents can be obtained.[16]

The converse of the Seebeck effect, the Peltier effect, whereby a junction of dissimilar metals is cooled when an electric current flows through it in the appropriate direction, has received very little application in the last 100 years. The use of bismuth telluride and related semi-conductors has given promising results in the production of refrigerating devices, and temperature differences of 85° C have been reported.[14] Not only could these advances have considerable influence in industrial and domestic refrigeration, but also be of great service in the cooling of electronic equipment.

Indium antimonide and indium arsenide possess high electron mobilities of the order of 75 000 and 28 000 cm²/volt sec respectively. They are therefore being used as the basis of new components utilizing either the Hall effect or the considerable change of resistance which occurs when they are subjected to the influence of a magnetic field. With either technique they may be used for the detection and measurement of magnetic flux, and devices utilizing the Hall effect can be used to detect fields as low as a few microgauss in strength.[17] In the communications field their greatest use may be in the production of linear suppressed carrier modulators.[18] If a Hall element is polarized with a carrier frequency and is placed in an electromagnetic system energized from a modulating source the sideband components can be extracted from the Hall electrodes (Fig. 19). Similar techniques can be used to produce an analogue multiplier. If the polarizing current and magnetizing current are proportional to the multipliers, the product appears at the Hall electrodes.[19, 20, 21]

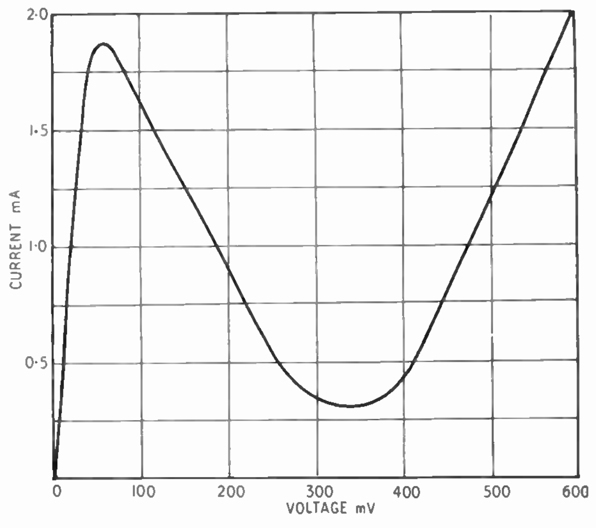


Fig. 18. Tunnel diode—resistance/bias relationship.

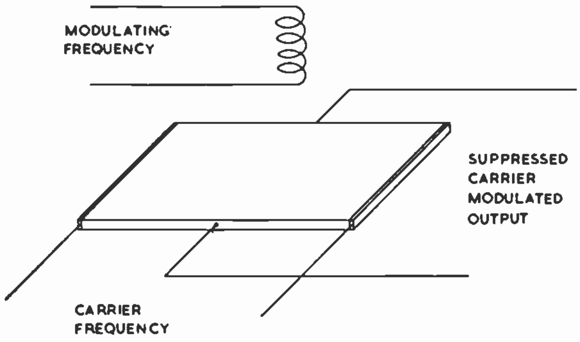


Fig. 19. Schematic diagram of Hall modulator.

6. Information Storage Systems

Mention must be made of the considerable improvements that are being made in the field of information storage. Devices using square hysteresis loop ferrites are being developed with greatly improved performances, not only because of improved materials but also by new circuit techniques. Equipment with complete cycle times of 200–300 millimicroseconds are being developed, and with the use of thin metal films, improvements of at least one order of magnitude are being sought.

This continuing requirement of higher operating speeds necessitates fundamental changes in the physical form of computers. Light travels approximately one foot in one millimicrosecond and an electrical current in an insulated wire is even slower. It can therefore be seen that connection wires of even a few feet in length between the storage device and its associated logic circuitry cannot be tolerated if acceptable phase delays are to be maintained, particularly if wires of similar function are not of equal length. The radio engineer has already solved the problem in high-frequency radio equipment, but, due to the much larger number of circuits involved, point to point wiring in a computer would not be very practical! It would seem therefore that the computer designer must turn to some of the new techniques of construction now being considered and known variously as micromodules, micro-circuits and solid circuitry which will not only give the reduction in size, but also the increase in reliability that he requires. These two reasons will also guide the telecommunication engineer towards their adoption in his equipment in the not too distant future.

7. Microminiature Devices

Many different ideas are being examined in order to produce a successful system of microminiaturization and methods of depositing material in thin layers are being actively exploited. In this connection the technique of making resistors by the vacuum deposition of Nichrome on to ceramic rods and cutting this layer in spiral form to give precise values of resistance is already established. Such resistors possess low temperature and voltage coefficients and are available in values of up to 2 megohms. Tin oxide on glass is also being developed to give useful resistors. Many metals can be deposited from aqueous solutions in the form of thin adherent films,[22] and these chemical methods may lead to new ways of making components or component assemblies. All the methods now under development for microminiature assemblies can be resolved into three basic systems of construction. The simplest and least sophisticated is the component substrate system in which a range of components is produced, each of similar shape, usually flat, and the size differing only in thickness. A group of these flat component elements are assembled by stacking and connections are made between the stacked assembly by soldering or brazing. Equipments are formed by interconnecting a number of modules. Densities of about 250 000 components per cubic foot are possible and components of this type are commercially available in the U.S.A.[23] (Fig. 20). It is a flexible system, but has the basic disadvantage that large numbers of connections still exist between components and therefore its reliability is suspect.

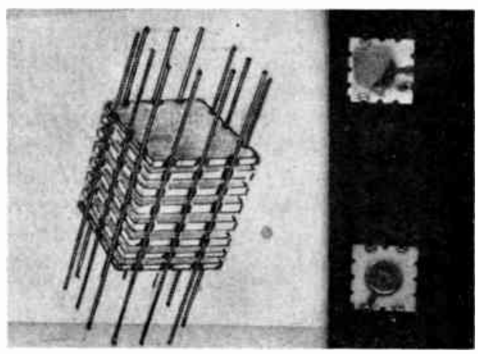


Fig. 20. Micromodules developed by R.C.A.

An improvement on this technique is the deposited circuit system and considerable development is taking place.[24] In this technique components are formed by evaporation or chemical deposition on the insulated substrates to form the passive parts of complete circuits; the only joints are those between substrates. An experimental two-stage amplifier in which the resistors and capacitors are evaporated on to a glass substrate is shown in Fig. 21.

The third technique, which is regarded as the forseeable ultimate is the solid circuit. In this a complete circuit is produced by changing the homogeneity of a piece of material, usually silicon, in such a manner that components are formed with the required parameters and physically so disposed that they are resistively or capacitively coupled in the required manner. Development of this technique is very active and a solid

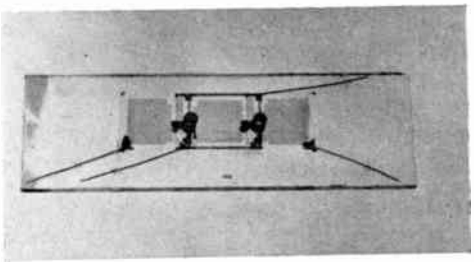


Fig. 21. Two-stage amplifier with vacuum deposited resistors and capacitors.

circuit oscillator is shown in Fig. 22. Packing factors of several million components per cubic foot are possible and the difficulties of interconnecting and cooling complete equipments are being resolved.

These three methods of construction mark the stages of a revolution in electronics. The first uses simple lumped components which can be manufactured as separate entities. It is mainly a means of obtaining equipment of minimum size by an automatic assembly technique. In the second method the components are mostly still distinct from one another, though distributed resistors and capacitors can be made, but the equipment for assembling the components is the same as that for making them; the manufacture of components and equipment must be merged. Finally in the solid circuit lumped components have disappeared and are replaced by the configuration and controlled properties of a semiconducting single crystal. It will take many years of development, and also much educating of circuit designers, before the solid circuit forms a major part of many equipments, but the extreme compression of circuit functions which it makes possible must eventually lead to its widespread use.

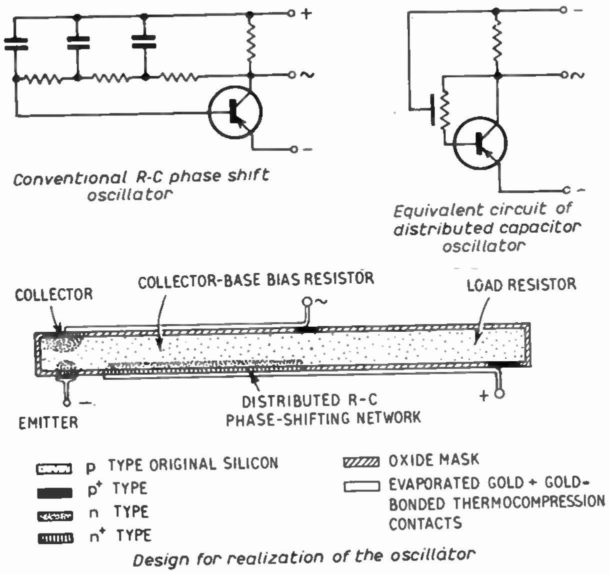


Fig. 22. A silicon solid circuit.

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Manuscript received 22nd August 1960 (Paper No. 605).

Background to the 1961 Convention

"RADIO TECHNIQUES AND SPACE RESEARCH"—OXFORD, 5th–9th JULY

International interest has been shown in the recent Conference held in Strasbourg when the possibility of a "European Space Launcher Club" was discussed. The British Minister of Aviation, the Rt. Hon. G. E. P. Thorneycroft, offered a substantial British contribution, both in cash and in the use of the *Blue Streak* missile, to form the basis of a combined space programme. Before agreement is obtained between the countries involved there will obviously be considerable discussion at political and engineering levels. The amount of international co-operation involved will be on a scale so far unparalleled in peace-time technological projects and will call for contributions from many different fields of science and engineering. The need for co-operation within British Industry has been emphasized by the agreement to form a consortium of several large aircraft and radio companies to be known as the British Space Development Corporation.

Institution members have special interest in the electronic techniques associated with the control and guidance of the satellite launcher. An even greater number of members are concerned with the "payload" itself and its associated ground equipment—whether this be transmitters and receivers for communication satellites or command transmitters and telemetry receivers for research satellites—and these subjects are featured in the Convention programme. The opportunities which will thereby be provided for discussing the various systems will prove valuable to all who may be concerned with the Commonwealth/European space project.

Independently of the Strasbourg decisions a satellite containing British instruments will be launched during the latter half of this year by the American *Scout* rocket. A wide range of geophysical measurements will be made possible by this launching and the results will augment the rocket soundings over the past few years obtained at Woomera in Australia through the British *Skylark* rocket.

All these research projects demand an understanding of the nature of the physical quantities to be observed in order that the radio equipment to record and transmit information to the ground shall be as efficient as possible. Thus at least two of the groups of papers to be included in the Convention will reflect these complementary aspects of the measurement to be made and the manner in which it is sent to Earth and evaluated. An interesting aspect of this question of observations on satellites is provided by the setting up of a tracking station in Great Britain. A brief description of the installation and its techniques for tracking satellites and receiving telemetered signals is given on page 150 of this *Journal*.

The striking advances in the entirely post-war science of radio-astronomy have played an invaluable part in furthering the use of satellites for both communications and especially for space research. A particular instance is the employment of such large radio telescopes as that at Jodrell Bank for tracking and communicating with satellites. Techniques developed for the reception of the very weak signals from the galaxies, notably the low-noise receiver of high sensitivity, are finding applications in receiving signals from passive relay satellites such as the Moon and the balloon satellite, *Echo I*. It was therefore decided by the Convention Committee that radio astronomy and its techniques were a vital part of space research in the broadest sense and ought therefore to be covered in the programme by specially invited papers.

It has been stated on many occasions, for instance at the Parliamentary and Scientific Committee's meeting on Space Research reported in the *Journal* of July last year, that the technological problems of a satellite programme would offer a challenge to engineers' ingenuity in evolving new techniques which would be applicable to other fields of engineering. While many members not at present professionally concerned with space projects will be attracted by the Convention programme as a whole, the papers dealing with satellite engineering will undoubtedly be received with an especial interest through their promise of solutions to difficult problems in microminiaturization and reliability.

It is intended that the programme of meetings shall include contributions from both the United States of America and the Soviet Union where so much of the pioneer work has been done in space research. This however does not exclude the desirability to include as many papers as possible from members who have already started work in this new field. The Convention Committee therefore particularly welcomes contributions from members either in the form of a contribution to symposiums, or on a specific aspect covered by the theme of the Convention. As it is hoped to publish a provisional programme in March, members wishing to contribute are urged to submit synopses as soon as possible.

A large number of provisional reservations have already been made. It is certain that not all delegates can be accommodated in Christ Church and arrangements for accommodation in other Oxford colleges will be announced in the March *Journal* when official registration forms will also be issued.

U.D.C. 621.316.721/2

Recommended Method of Expressing Electronic Measuring Instrument Characteristics

6. STABILIZED POWER SUPPLIES †

Prepared by the Technical Committee of the Institution and based on a report compiled by C. S. Fowler (Associate Member).

Introduction

This is the sixth set of recommendations in a series which has the objective of influencing the uniformity of presentation of information on the features, characteristics and performance of electronic measuring instruments and thus assisting in their comparative assessment and selection by potential users. The establishment of standards of performance is not an objective of these recommendations.

The characteristics dealt with in this set of recommendations include all forms of stabilized and regulated power supplies. Although not measuring instruments these equipments are an essential part of measurement.

Table of Contents

FEATURE		METHOD OF EXPRESSION	REMARKS
		Part 1.—GENERAL DETAILS	
1.1	**Input power supply requirements**	..volts d.c./a.c. .. c/s and/or battery .. watts (voltage change ± .. %; frequency change ± .. %)	The maximum power consumption at full rated load must be given. Maximum voltage and frequency variations for which the stated accuracies hold good must be given.
1.2	**Temperature range**	.. °C to .. °C	Maximum ambient temperature range for which the stated accuracies hold good assuming nominal value of power supplied.
1.2.1	Internal temperature	.. °C	Maximum allowed at full load.
1.3	**Construction and finish**		Where these features conform to a particular specification the latter should be named.
1.4	**Valve and/or transistor complement**	Type numbers.	State if special selection is required.
1.5	**Type of input and output connections**		Full description to be given.
1.6	**Accessories**		Full details to be given.

† Approved by the Council for publication on 13th July 1960 (Report No. 20).

FEATURE		METHOD OF EXPRESSION	REMARKS
1.7	**Dimensions**	Height .. in. (.. cm) Width .. in. (.. cm) Depth .. in. (.. cm)	Over all projections.
1.8	**Weight**	.. lb (.. kg)	With batteries if appropriate.
	Part 2—ALTERNATING CURRENT AND/OR VOLTAGE STABILIZERS		
2.1	**Basic type of control circuit**		Brief description of mode of operation, whether mechanical, magnetic, electronic, etc.
2.1.1	Reference standard		Standard cell, discharge neon, Zener diode, etc.
2.2	**Output**		
2.2.1	Voltage	.. volts r.m.s. to .. volts r.m.s.	Range of output voltage control.
2.2.2	Current	.. amps r.m.s.	Maximum current at maximum voltage with unity power factor.
2.2.3	Impedance	.. ohms	
2.2.4	Power factor	.. to ..	State the limit of permissible power factor variation.
2.3	**Stability**	After .. minutes	Give time required to reach thermal equilibrium.
	Effect of variation in		
2.3.1	Input voltage	..% change of output volts/current for .. % change of input volts.	State maximum pulse load allowed.
2.3.2	Input frequency	..% change of output volts/current for .. % change of input frequency.	
2.3.3	Output load	..% change of output volts/current for a stated change of output load.	
2.4	**Speed of response** To changes in		
2.4.1	Input voltage	.. seconds.	Recovery time to nominal voltage for 1%, 5% and 10% change in input voltage or load current.
2.4.2	Load current	.. seconds.	
2.5	**Distortion of output wave form**	Form factor.	Harmonic content can be given if preferred.
2.5.1	Change of output waveform with input frequency	Change of form factor for given % change of input frequency.	
2.6	**Overall efficiency**	.. %	$\frac{\text{Output}}{\text{Input}} \times 100\%$ at unity load power factor.
2.7	**Metering facilities**	YES/NO.	State parameters metered.
2.8	**Overload protection**	YES/NO.	Type (fuse, thermal trip, etc.).

FEATURE		METHOD OF EXPRESSION	REMARKS
	Part 3—DIRECT CURRENT AND/OR VOLTAGE STABILIZERS		
3.1	**Basic type of control circuit**		Brief description of mode of operation, whether mechanical, magnetic, electronic, etc.
3.1.1	Reference standard		Standard cell, discharge neon, Zener diode, etc.
3.2	**Output**		
3.2.1	Voltage	.. volts to .. volts.	Range of output voltage control.
3.2.2	Current	.. amps to .. milliamps.	Maximum and minimum current at maximum volts.
3.2.3	Impedance	.. ohms at d.c. .. ohms at .. c/s.	A graph of impedance against frequency, for various loads, should be given.
3.3	**Stability**	After .. minutes.	Give time required to reach thermal equilibrium.
	Effect of variation in		
3.3.1	Input voltage	..% change of output volts/current for ..% change of input volts.	State maximum pulse load allowed.
3.3.2	Input frequency	..% change of output volts/current for ..% change of input frequency.	
3.3.3	Output load	..% change of output volts/current for a stated change of output load.	
3.4	**Speed of response** To changes in		
2.4.1	Input voltage	.. seconds.	Recovery time to nominal voltage for 1%, 5% and 10% change in input voltage or load current.
2.4.2	Load current	.. seconds.	
3.5	**Ripple and hum content**	.. millivolts under full and zero load conditions.	Frequency of unwanted ripple should be given.
3.6	**Overall efficiency**	.. %	
3.7	**Metering facilities**	YES/NO.	State parameters metered.
3.8	**Overload protection**	YES/NO.	Type (fuse, thermal trip, etc.).

List of the Recommendations in this Series

1. "Amplitude-modulated or frequency-modulated signal generators", (January 1958).
2. "Cathode-ray oscilloscopes", (January 1959).
3. "Low frequency generators, (March 1960).
4. "Valve voltmeters", (April 1960).
5. "A.C. Bridges", (August 1960).

The dates given are the issues of the *Journal* in which the particular recommendation appears; separate reprints may be obtained from the Institution, price 1s. 6d., post free.

APPLICANTS FOR ELECTION AND TRANSFER

As a result of its meeting on 31st January the Membership Committee recommended to the Council the following elections and transfers.

In accordance with a resolution of Council, and in the absence of any objections, the election and transfer of the candidates to the class indicated will be confirmed fourteen days after the date of circulation of this list. Any objections or communications concerning these elections should be addressed to the General Secretary for submission to the Council.

Direct Election to Member

JAMES, Ivanhoe John Penfound, B.Sc. *London, W.5.*

Transfer from Associate Member to Member

CATTLE, William Frederick. *Salisbury, Southern Rhodesia.*

Direct Election to Associate Member

CONWAY, Dennis John. *London, S.W.16.*
HAMILTON-JONES, Maj. John, R.A. *London, S.W.1.*
HARPER, Sqdn. Ldr. James Fredrick Henessy, R.N.Z.A.F. *Wellington, New Zealand.*
WATKIN, John Cyril, B.Sc.(Eng.) *Salisbury, Southern Rhodesia.*

Transfer from Graduate to Associate Member

BARBER, Flt. Lt. Kenneth, R.A.F. *Stockport, Cheshire.*
BARNES, Derek Albert. *Mitcham, Surrey.*
CHAPMAN, Maurice George. *Birchington, Kent.*
CLARK, James Oliver, B.Eng. *Bracknell, Berkshire.*
DUNNETT, Paul Wesley. *Farnborough, Hants.*
JONES, David Kenton, B.Sc. *Evesham, Worcs.*
SIBBALD, John Scott. *Edinburgh 4.*
SUCKSMITH, Alan Vaughan. *Newport, I.o.W.*
TOURNIER, John. *High Wycombe, Bucks.*

Transfer from Student to Associate Member

RITCHIE, Robert. *Farnham, Surrey.*

Direct Election to Associate

DISSANAYAKE, Flt. Lt. Callistus, R. Ceylon A.F. *Calne, Wiltshire.*
JONES, Thomas Islwyn. *Hatfield.*
MANCHESTER, John Kay. *London, W.4.*
WARWICK, Kenneth Francis. *Chigwell, Essex.*

Direct Election to Graduate

ARCHBOLD, Brian David. *Uxbridge, Middlesex.*
ARMITAGE, Stanley Tetley. *Bradford 6.*
BROWN, John Robert. *Chalfont St. Giles, Bucks.*
BUMFORD, Brian Arthur. *Reading, Berks.*
CARTER, Malcolm Keith. *Bournemouth, Hants.*
CHALLENGER, Michael Trevor. *Stafford.*
DUNK, Bernard Edward. *Windsor, Berks.*
FERLA, John Anthony. *Birmingham 31.*
FOWLER, Donald Geoffrey. *Durham City.*
FREER, Colin George Harry. *Kettering, Northants.*
GIBBS, Terrence Walter. *London, S.E.9.*
GIBSON, Michael. *Chelmsford, Essex.*
GLOVER, Laurence Owen. *London, S.E.14.*
GRICE, Peter Anderson. *Hale Barns, Cheshire.*
HICKS, Terrence Albert. *Great Malvern, Worcs.*
KEOWN, Douglas Grierson. *East Kilbride, Lanarks.*
LINDLEY, James Vernon. *Manchester.*
NG, Meng Chiang. *Singapore 6.*
PROBERT, Peter Frank. *H.M.S. Collingwood.*
RAMSAY, James. *Reading, Berks.*
RYLEY, John Edwin, B.Sc.(Eng.). *Wimborne, Dorset.*
RUDDOCK, Alan Graham. *Chelmsford, Essex.*
RYLEY, Derek Vernon, B.Sc.(Eng.). *Wimborne, Dorset.*
RUAUX, Terry Charles Edward. *Newbury, Berks.*
SINCLAIR, John Alexander. *Coventry.*
THOMAS, Trevor. *Basingstoke.*
WALLER, James Raymond. *Guildford, Surrey.*

Transfer from Associate to Graduate

CHRISTMAS, Kenneth James. *Colchester, Essex.*

Transfer from Student to Graduate

ADEBOYEJO, Michael Oluseyi. *London, W.9.*
BENNETT, Wilfred. *Stoke-on-Trent.*
DAVIES, William Peter. *Luton.*
HORNE, Leslie. *Leeds 17.*
KING, John. *Ilford, Essex.*
LUTER, Michael Edward. *Cowes, I.o.W.*
ONI, David Adelegan Omofadesola. *London, S.E.27.*
ONYIA, Augustine Ndudi. *Lagos, Nigeria.*
WALTER, Robert William. *Leicester.*

STUDENTSHIP REGISTRATIONS

The following students were registered at the 29th November and 4th January meetings of the Committee. The names of a further 25 students registered at the 4th January meeting together with 29 students registered at the 31st January meeting will be published later.

HAMMERSLEY, Stanley F. *Uckfield, Sussex.*
HAMMOND, Edward. *Slough.*
HARDING, Nigel Brynmor. *Hampshire.*
HARRISON, Brian. *Northfleet, Kent.*
HILLMAN, Peter. *Rainham, Essex.*
HOLLOWAY, Ronald. *Hove.*
HOO, Yuen Chong. *Kuala Lumpur.*
IYENGAR, Sreejayanthi, Miss. *Jabalpur, India.*
JAGTAP, Pralhad Tikaram. *Indore, India.*
JOHNSTON, Kevin James. *Auckland.*
JONES, Denis C. *London, E.17.*
JUNGMANN, Josef. *Haifa, Israel.*
JURGENS, Desmond Harry. *Northern Rhodesia.*
KASHIKAR, Prakash Raghunat. *Bombay.*
LEAFE, John. *Annan, Dumfriesshire.*
LING, Shun Ki. *Hong Kong.*
LO, Loke Yee. *Kuala Lumpur.*
MacLEOD, Donald F. *Isles of Lewis.*
McQUIRE, Adrian Frank. *Romford.*
MacRAE, John Alick. *Montreal.*
MARCHANT, Raymond Jack. *Southampton.*
MARR, Robert Whyte. *Chadwell Heath, Essex.*
MENKITI, Alexander Ifeanyi. *Lagos.*
MOHANTY, Kiran Kumar. *Orissa, India.*
MOODY, Robert W. *Burgess Hill, Sussex.*
MOORE, Telford, B.Sc. *Huddersfield.*
MUKERJEE, Sudhendu K. *Kanpur, India.*
NARAYANAN, R., B.Sc. *Trichinopoly, India.*
ODU, Alatunji Akanbi. *Lagos.*
ONOZIE, Baldwin O. *Lagos.*
OSULA, Rufus Bolarinde. *Lagos.*
OWUSU, Emmanuel. *London, W.5.*
PALMER, Donald V. *Seven Islands, P.Q., Canada.*
PANDEY, Sankata P., M.Sc. *Basti U.P., India.*
PARABRAHMA RAO, D. *Bangalore.*
PARRY, Ronald I. *Christchurch, New Zealand.*
POPE, Phillip John. *Watford.*
PRICE, David Wilfred. *Edinburgh.*
RAEMESHVAR SINGH, Panjin S. *Singapore.*
RAGHUVEER, B., M.Sc. *Bangalore.*
RAMESH, K. M. *Madras.*
RAY, Sunil Kumar. *Bangalore.*
ROBERTS, James Alfred. *London, E.4.*
SAEED, Mohamed Abdul. *London, S.E.5.*
SALIM-KHAN, Mohammad, B.A. *Robertsbridge, Sussex.*
SAROJINI, Miss Kalphathy Ananthakrishna Iyer, M.A., B.Sc. *Bombay.*
SHARMA, Kamlesh Kumar Khayaliram, B.Sc., M.Sc. *Ratlam, India.*
SINHA, Om Prakash, M.Sc., *Bihar, India.*
SUKHWANI, Assan Hotchand, *Bombay.*
SWANI, Bhopinder Singh, B.A. *Southall.*
TOMASZEWSKI, Eligiusz E. E., *New Malden.*
UDAYAN, Chettipparambil Kandassan, B.Sc. *Ernakulam, South India.*
VEERARACHAVAN, S., B.Sc. *Madras.*
WALKER, Ernest John. *Weston-super-Mare.*
WALL, Reginald Victor. *Cheltenham.*
WHALL, Terence Edward. *Barking.*
WILLIAM, Amalraj, B.Sc. *Madras.*
ANAND, Sushil. *Delhi, India.*
ANUPURATH, Ramanunni. *Palaghat, India.*
ASHIRU, Rasaki. *Nigeria.*
AUQIL, Hafiz Mohd. *London, E.1.*
BACON, Maurice. *Padstow, Cornwall.*
BALASUBRAMANYAN, Pallassana N. *Poona.*
BARRY, Roy. *Blackpool, Lancashire.*
BHAKTHAVATHSALU, Chengature. *Poona.*
BHALLA, Bawa Guru. *Bangalore.*
BHATIA, Dayaldas. *Saurashtra, India.*
CARPENTER, Brian Robert. *Lowestoft.*
CHAN, Fook Cheong. *Singapore.*
CLANCY, Robert Alexander. *Lanarkshire.*
COXAN, David John. *Liverpool.*
DACK, Ronald Norman. *Watford.*
DAVEY, Roy Cecil. *Monmouthshire.*
DAVIS, Charles Emanuel, B.Sc., *London, S.W.17.*
FANTINI, Arthur Brian. *Hull.*
FUROIS, Philippe. *New York.*
GAONKAR, Ramesh S., M.Sc., B.Sc. *Bombay.*
GREEN, Robert Garnett, B.Sc., *Stevenage.*
GRIFFITHS, David Alston. *London, S.W.6.*
HALL, Ernest. *Basildon, Essex.*
HARRISON, William. *Oldham.*
HOARE, Anthony. *Reading, Berkshire.*
HYATT, James. *Potters Bar.*
INDRAPAL SINGH. *Aligarh, India.*
JONES, Robert. *Wolverhampton.*
JUWEMAN, John. *Bermuda, B.W.I.*
KRUEGER, Horst. *Lawrence, Australia.*

U.D.C. 621.37/9.004.6: 623

Maximizing Electronic Reliability

By

MORRIS HALIO, B.Sc.†

Presented at a Symposium on New Components held in London on 26th–27th October 1960.

Summary: Every piece of military electronic equipment passes through various phases in its normal life cycle. These are planning, design and development, pilot production, manufacture, transportation, storage, operation and maintenance. Each of these stages is replete with opportunities for the introduction of unreliabilities. The paper points out the pitfalls which may be encountered and makes specific recommendations to avoid these so that the full amount of potential reliability may be realized in the final equipment.

1. Introduction

By this time most engineers have been made aware of the growing complexity of weapon systems utilizing countless electronic circuits with myriads of components and the terrifying reliability problems that arise as a consequence thereof. These are well known facts; the crux of the matter is what can we do to remedy the situation? The reliability problem with its many facets is reminiscent of the many-headed hydra. Each of these heads must be removed to conquer the beast. If we were to trace a piece of equipment through its life cycle we might arrive at a flow chart such as the following:

PLANNING → DESIGN AND DEVELOPMENT → PILOT PRODUCTION → MANUFACTURING → TRANSPORTATION → STORAGE → OPERATION AND MAINTENANCE

Each of these stages presents an opportunity for additional unreliabilities to be introduced. It is obvious that if the design is such as to limit the maximum potential reliability to a certain value, then poor manufacturing processes or the deleterious effects of storage, for example, can only serve to reduce the ultimate reliability of the equipment. It is therefore imperative to minimize the unreliabilities introduced by each step in the process.

At this point some of the terms used in this paper must be defined. The first one, of course, is "reliability". Definitions of this term vary from some long and complicated ones to the simple one, "When you press the button, it goes." The definition the author prefers is that employed by one of the task groups of A.G.R.E.E. (Advisory Group on Reliability of Electronic Equipment of the Office of the Assistant Secretary of Defense). This is:

"Reliability of an item is the probability that it will perform without failure a specified function under specified test conditions for a required period of time."

Mathematically this can be expressed as,

$$R(t) = \exp(-t/m),$$

where $R(t)$ is the reliability, t is the variable time and m is referred to as the reliability index. The latter is defined as the average measure of the equipment failure rate expressed in mean-time-between-failures. The reciprocal of this quantity is known as the failure rate and is most conveniently expressed as number of failures per thousand hours.

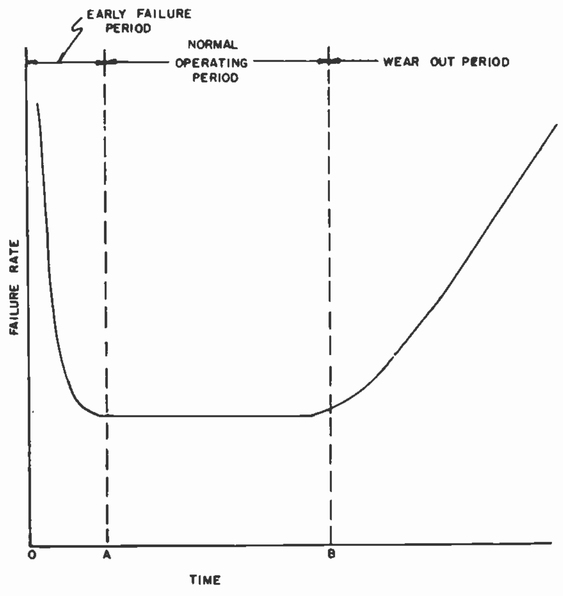

Fig. 1. Failure rate of equipment vs time.

Figure 1 depicts a typical statistical curve of the variation of failure rate during the life of an equipment. The high rate of early failures is attributable to poor components control, manufacturing techniques, inspection and quality control. At time A the defective components have been eliminated and the failure rate is essentially constant until time B when

† U.S. Army Transportation Materiel Command, St. Louis, Missouri.

the failure rate begins to increase, signifying the end of useful life of the equipment.

The terms employed for the various subdivisions of an equipment are still not fully standardized and the following definitions which are adopted in this paper are modifications of those listed in DOD Directive 3232.2.[14]

COMPONENT: An item which cannot be disassembled without destroying its identity; e.g. resistor, capacitor, switch, relay, socket, bearing, bolt.

SUB-ASSEMBLY: An aggregation of component parts mounted together for convenience and incapable of performing any function prior to being incorporated into an assembly; e.g. a terminal board with parts mounted on it, an i.f. transformer with tuning slug and mechanism.

ASSEMBLY: A combination of component parts or sub-assemblies or both capable of performing a function; e.g. amplifier, oscillator, modulator, filter, power supply, junction box.

UNIT: An aggregation of assemblies, constituting an element of an equipment and performing a function necessary to the operation of that equipment; e.g. transmitter, receiver, rotating antenna, frequency standard.

EQUIPMENT: A group of components capable of performing a specified function; e.g. a radar set, a gun director.

SYSTEM: A combination of equipments which have the capability of performing a mission; e.g. an anti-aircraft system consisting of radars, guns, missiles, interceptor aircraft, etc.

In the U.S.A. the subdivision formerly known as "component" is now referred to as "part" while the term "component" is reserved for designating a group of assemblies (or "unit").

2. Planning

The first phase of the reliability programme is the planning stage. It is necessary that quantitative specifications for equipment reliability be incorporated into the development contract. The present low level of reliability may be partly ascribed to failure to do so. In the past, a manufacturer who designed a new system has had to meet certain performance specifications. However, he has been under no legal obligation to include reliability among these. As a result, reliability has been treated as an afterthought. Long experience has shown that this is too late to improve reliability. Once the design has been settled, the failure rate of electronic equipment cannot be appreciably decreased by remedying features giving trouble. High reliability cannot be achieved unless this factor is taken into account during the preceding stages.

Reliability requirements should originate with the groups responsible for the operational requirements and military characteristics of the various services, since it is through these groups that the services must determine how they intend to accomplish their mission. These requirements must then be incorporated into the development contracts for new equipment. Proper planning is the foundation on which the reliability structure is based.

3. Design and Development

Design and development follow the planning stage. The reliability of the completed equipment will depend on that of the components employed as well as the circuitry in which they are utilized. It is well known that the overall reliability of an equipment where the components are placed in series† can be expressed by the equation

$$R_{\text{overall}} = R_1 \times R_2 \times R_3 \times \ldots \times R_n$$

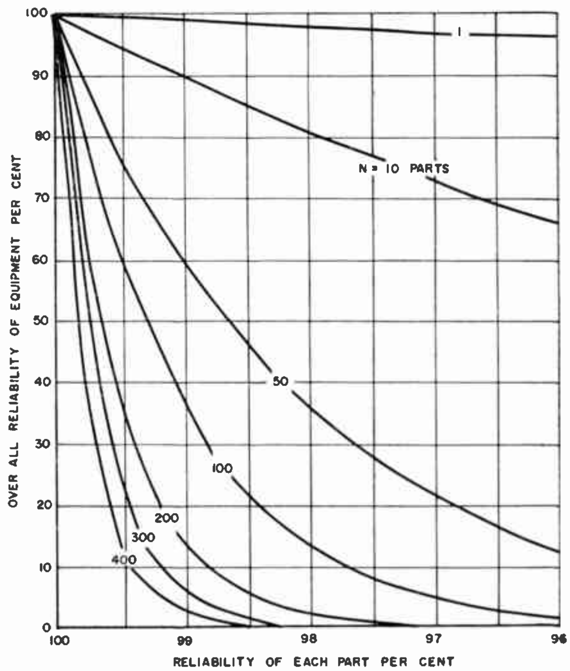

Fig. 2. Overall reliability as a function of complexity and reliability of parts.

i.e. the overall reliability is the product of the individual reliabilities. The simplifying assumption has been made that there are no reliability interactions among the various components. Evidently, for very complex equipments, the reliabilities of individual

† A component is a series component if its failure would cause the entire equipment to fail. It is a parallel component if its failure would not necessarily lead to failure of the equipment, since it is shunted by another component.

parts must be extremely high if the overall reliability is to be tolerable. Figure 2, which has been adopted from ref. 3, shows the relation of overall reliability to individual reliabilities for various degrees of equipment complexity. For simplicity, the individual reliabilities have been made equal. Notice that, for example, an equipment of 400 components each 99% reliable only has a 2% overall reliability. This emphasizes what is probably the most important concept in the study of reliability, namely, that individual components of a complex equipment must be of the very highest reliability. This means that the margins between the strengths and stresses must be sufficiently large. By stresses are meant not only mechanical forces, but other parameters such as voltage, current, frequency, temperature, humidity, acceleration, vibration, etc., to which a component is subjected in use. The strengths are the values of these parameters at which failure will occur under the given conditions.

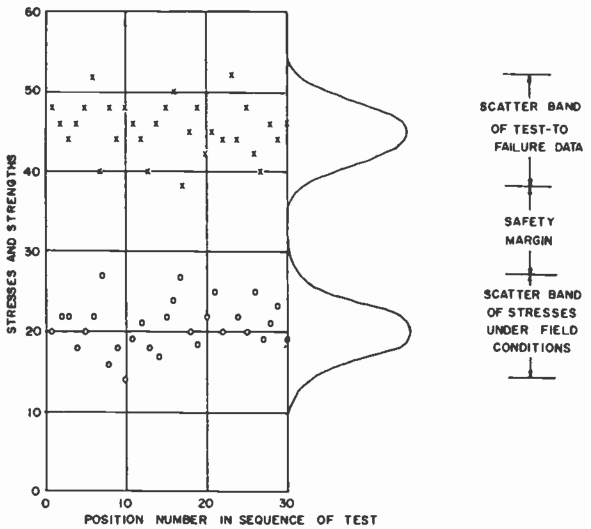

Fig. 3. Distribution curves of strengths and stresses.

To determine whether a component to be used in an equipment is of acceptable reliability a stress-strength analysis is recommended. The following procedure is employed. A stress scatter diagram is constructed as in Fig. 3 depicting the stresses to which the component will be subjected in the intended application. These data will have been obtained from field measurements. A frequency distribution curve is drawn and the mean and standard deviation calculated. Tests-to-failure are then conducted on a representative sample of the component whose use is contemplated and the strengths plotted. The frequency distribution curve, the mean and the standard deviation for the strengths are obtained. To determine the allowable margin between the mean stress and mean strength, the standard deviations of stress and strength are multiplied by suitable factors depending on the required part reliability and the products are added. Thus, the total permissible margin between the strength and stress means can be expressed as:

$$M = K_1 S_1 + K_2 S_2$$

where M is the margin, K_1 and K_2 are the strength and stress factors, S_1 and S_2 being the corresponding standard deviations. If the actual margin is less than the permissible margin, it means that the component will have to be redesigned or replaced with a more reliable component. Stress-strength analysis of this type is of extreme importance in the effort to attain high reliability.

It would be extremely desirable to standardize components of high strength and to have this information assembled in handbooks available to designers. A start has been made in this direction, but the trend will have to be greatly accelerated to meet the needs of the military. Vitro Corporation, RCA, Battelle Institute and Inland Testing Laboratories are among those who are doing pioneering work in this field in the U.S.A.

Sub-assemblies, assemblies and units should also be subjected to tests-to-failure. However, the purpose of testing these is to discover failures caused by specific assembly effects, such as local resonances and ambient temperatures. Therefore testing of these items is recommended only after it has been determined that components of extremely high reliability have been employed under conditions of adequate margin of safety. Otherwise this type of testing becomes very cumbersome and failures attributable to component unreliability mask those caused by assembly effects.

Stress-strength analysis depends upon testing of components to failure as contrasted to testing of complete equipments under operating conditions. Unfortunately there has been too much reliance on the latter procedure as a means of seeking the achievement of reliability. This is to be deplored since testing-to-failure furnishes a much better means of attaining this goal. For one thing, it makes it possible to determine very quickly the modes of failure and permit redesign so that reliable components can be used in the equipment. The old methods depending on failure reporting of equipments tested under normal operating conditions would take forever and a day to accomplish the desired result. In addition, testing-to-failure is far cheaper, since this method requires substantially fewer tests. Extensive flight testing of missiles, for example, can be rather expensive. Even then, the ultimate cause of failure is often not discovered. Or to put it another way, testing-to-failure means that we can buy much more reliability for a fixed amount of money.

One of the ways in which component reliability may be improved is for the components designers to refrain from designing universal components. Design of a single component for several applications with widely differing specifications tends to make the reliability for each application lower than if a different type were built for each of these. A component is generally designed for universality of application for two reasons. One is lower cost because of high quantity of production. The other is, that the control processes that accompany mass production tend to improve the quality and consequently the reliability of the product. However, there is a certain level of production beyond which the quality remains essentially constant. Once this is reached, the faults of the multiplicity of functions of a universal part become evident. For example, in the case of valves, a valve may be used in a d.c. amplifier or in a blocking oscillator. Clearly, the specifications are different for these applications. By designing a valve which is applicable to both of these uses, the reliability for each suffers. There is certainly sufficient demand for each type so that a different valve can be built for each application. It is therefore recommended that component designers originate different types for widely varying uses.

Another step the circuit designer can take to maximize reliability is to select component types which have higher inherent reliability. For example, vacuum relays can be used in place of other types. Employment of solid-state devices such as transistors imparts certain advantages such as low heat dissipation and resistance to shock in addition to long life. Probably the greatest advance to date in this direction lies in the field of molecular electronics. This type of device eliminates the need for internal connections and should make it possible to increase the reliability tremendously.

The total effect of components tolerances plus drift due to ageing may cause failure of a circuit in operation. Thus an oscillator may shift its frequency out of tolerance or may stop oscillating entirely; a flip-flop may reach such a condition that a prescribed pulse may fail to trigger it. To prevent such an occurrence, a design method known as marginal checking (developed by Lincoln Laboratory) is recommended. In this the allowable variation of a component is determined as a function of a selected circuit parameter, usually a supply voltage or a trigger voltage. In practice, the tolerance of one of the components in the circuit is plotted against the variation in this marginal-checking parameter, as shown in Fig. 4. For various values of component deviation, the supply or trigger voltage is varied until the circuit fails to perform according to specifications. The locus of failure points separates the failure region from that of normal operation. In this manner, not only can the proper design centre value be determined but the allowable tolerances as well. Universal employment of marginal checking by equipment designers is decidedly recommended.

The foregoing discussion has been concerned with the reliability of components. Some of the principles involved in the integration of these components to form reliable equipment will now be enumerated.

The first and most obvious precaution is to keep it simple. Equipment should not only be simple in design, but simple to operate. One of the causes of equipment unreliability is the maladjustment of controls because of the excessive number of front-panel adjustments which require an engineer's training

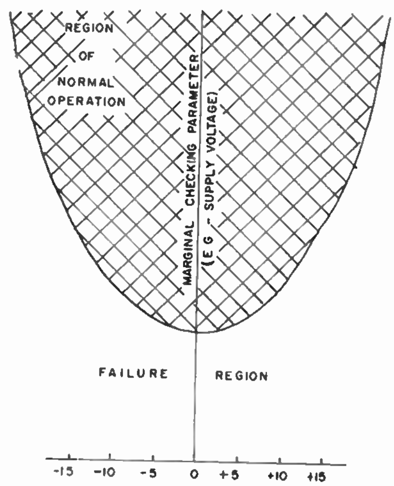

Fig. 4. Marginal checking-locus of failure points.

to be correctly set. This is due to a design tendency to include controls which, when properly adjusted, increase equipment performance levels somewhat, but when maladjusted, reduce the equipment function to almost inoperable levels.

In addition to operability, the equipment should be designed for a high level of maintainability. The latter is defined as the reciprocal of the mean net time to repair failures. Expressed mathematically:

$$M = \frac{1}{\bar{x}} \qquad \text{where } \bar{x} = \sum_{i=1}^{n} \frac{x_i}{n}$$

Because of the increasing complexity of equipment and the generally decreasing skill level of service personnel, it is necessary to make equipment easy to maintain. This presupposes the adoption by the designer of a disposal-at-failure maintenance philosophy. Circuits are designed as modules for ease of fault tracing and replacement. In accordance with this philosophy are the employment of printed circuitry, encapsulation and miniaturization. It is recommended that specific maintainability requirements be included in development contracts for equipment.

The employment of theoretical reliability prediction in the initial design stages is invaluable. The technique consists of the construction of a functional diagram of the equipment in the form of blocks or units. The latter are assigned reliability values which are derived from known component failure rates, and an overall reliability figure is calculated. This permits the evaluation of potential designs on paper, thus weeding out the undesirable ones. This method not only saves time and money but results in a design which is inherently more reliable.

Another important principle is the practice of conservatism of electronic circuit design. Components should be derated and valve voltages should be selected so that the lowest values which give the required performance will be employed. The latter step improves reliability in several ways. Component failure is minimized because of reduced peak currents, lowered potential stress and decreased heat dissipation. The likelihood of avalanche failure is greatly reduced. In addition, the consequent restricted energy level reduces the incidence of parasitic oscillations.

Redundancy is one method employed as a reliability measure. Two or more identical components are placed in parallel so that failure of one component will not make the equipment inoperative. It should be remembered that in many cases it is not possible to place redundant components directly in parallel, so that a switching arrangement is required. The latter may introduce unreliabilities of its own which can severely reduce or negate the advantages gained by the use of redundant elements. In addition, there is a penalty to be paid of increased size and weight, not to mention cost of the equipment. Redundancy is a necessary evil and is recommended only for critical components where every effort to achieve the required reliability has failed.

Reliability considerations require that the components in a circuit be integrated into a package which is designed with a view towards optimizing ruggedness and thermal adequacy. With respect to ruggedness, the design should be such as to restrict the maximum vibrational transmissibility (transmissibility is the ratio of induced to applied vibration amplitude) to a value as near to unity as possible. For example, the use of the clamped-clamped type of assembly, where mounting boards are clamped at both ends, rather than the cantilever type, is recommended. The basic principle of adequate thermal design is to make the total equivalent thermal resistances from all heat generating components to the thermal sink or environment as low as possible. That is, adequate conduction, convection and radiation paths should be provided to dissipate the heat. In most circuits, the valves are the principal heat-generating components and their operating temperatures generally exceed the permissible operating temperatures of the other components. Therefore, thermal adequacy begins with valve location. It is desirable to locate them as far as possible from the components having the lowest permissible operating temperatures. Employment of equivalent thermal circuit diagrams in a paper analysis is of great assistance in minimizing cut-and-try methods in design. Proper packaging for ruggedness and thermal adequacy is a very important step towards equipment reliability.

Employment of standardized electronic circuitry by equipment designers can be very effective in achievement of high equipment reliability. The National Bureau of Standards and the Navy Electronics Laboratory have designed a variety of electronic circuits with the emphasis on a high order of reliability. These have been published in the "NBS Preferred Circuits Handbook" and the "NEL Reliability Handbook". A recent study of 83 pieces of Navy electronic equipment showed that 30% of the circuitry could be performed by the circuits listed in these handbooks. It is recommended that the development of preferred circuits be extended and that equipment designers get into the habit of using these as much as possible. This may be a blow to the pride of designers who make a fetish of originality but it will also be a blow struck against unreliability in their equipment. The use of standard assemblies which may be used in many equipments leads to a further gain in reliability because of the improved quality control which accompanies higher production levels.

Proper liaison is an important factor and its omission can contribute to unreliability. Liaison between designer and user is desirable to acquaint the designer with the user's environmental, operating and maintenance problems. This is much more important with military than with commercial equipment since, in the case of military equipment, a specific number of equipments are contracted for and manufactured before there is feedback from the user to the producer informing the latter of equipment short-comings whereas in the case of commercial equipment, feedback begins with the first shipments of equipment so that design weaknesses can be corrected before large scale production takes place.

Liaison among the various groups involved in the development of an equipment is important, too. RCA uses an elaborate system to ensure maximum reliability. After the development contract is awarded, the design engineer must justify his ideas before a panel of experts—reliability engineers, components designers, specialists in shock, vibration and heat, circuit designers, etc. This is done before the design is started and also after the "breadboard" is ready. When the model is constructed, it is thoroughly tested, the results being reviewed by experts and analysed in terms of the whole system. Weak points and lack of reliability are spotted. Undesirable interaction effects between various components of the equipment are eliminated. If found necessary, other tests are recommended, circuits are modified, packaging is changed. In the end, the equipment functions according to specified requirements. All of this review may seem to be unnecessarily time-consuming. But this procedure produces very large savings in re-engineering costs and what is more important results in a highly reliable product. Emulation of this philosophy is definitely recommended for all developers of military electronic equipment.

4. Pilot Production

Following development is pilot production of the equipment, the primary purpose of this stage being to enable the customer to get an idea of what may be available from regular production. It is also of benefit to the manufacturer in that it permits him to prove out the tooling and manufacturing processes.

In addition to the usual performance tests, a battery of environmental tests should be carried on to determine the reliability. Among these should be temperature and input voltage variation, vibration and off-on cycling as a minimum. Other environments selected depend on the corresponding service conditions and may include humidity, salt spray, sand, dust, shock, radiation, etc.

Because of the inherent characteristics of the pilot production process, the output is unavoidably heterogeneous and the reliability tests are indicative of the capability of the manufacturing process rather than of acceptability.

5. Manufacture

The most obvious method of assuring that unreliabilities do not creep in during the manufacturing process is by practising adequate quality control. Another step which can be as important is to survey and rate the vendors in the field, qualifying their products.

Automation can be of help in improving reliability. Investigations indicate that mechanized assembly techniques for electronic equipment tend to maximize reliability. These techniques include processed wiring circuitry, mechanized insertion of components, automatic mass soldering and automatic functional testing. Mechanized production and testing methods possess an advantage over manual methods in that the former avoid the irregularities in techniques and materials of the latter, resulting in improved reliability.

One of the reasons for the existence of unreliable equipment is the tendency to rush it into production before the development has really been completed. Present procurement practices which aim to provide accelerated delivery of electronic equipment tend to minimize the time allowed for adequate reliability evaluation. This telescoping of development with procurement is accomplished at the expense of a sound reliability test programme during the vital engineering phase and must necessarily be reflected in decreased reliability of the end product. Therefore, it is recommended that production be postponed until adequate engineering tests prove that the item in question fully meets the reliability requirements.

6. Transportation

The transportation phase furnishes an excellent opportunity for introduction of unreliabilities. The military services have experienced substantial damage to equipment during shipping, resulting from improper packaging and packing. Since the damage which occurs is not always detectable and therefore repairable, incipient failures may easily occur. Proper packaging and packing is an important link in the reliability chain.

The steps taken to ensure proper packaging design of the equipment to withstand operating shock and vibration will also serve to protect it during transportation. In addition it is necessary to investigate the shock and vibration experienced by equipment packed and shipped in containers. It is recommended that instruments be developed which will record the amplitudes and durations of shocks to which equipments are subjected in shipment. These should be of a type which will operate unattended for a period of several weeks. In addition, it will be necessary to determine specific dynamic values for a wide variety of cushioning materials for the use of designers of shipping containers.

The recommended research in packaging and packing should lead to increased operational reliability of electronic equipment.

7. Storage

Since production contracts provide for sufficient numbers of equipments not only to meet the current operational requirements but to allow an adequate reserve, it is obvious that the excess must be kept in storage for appreciable periods of time. This process subjects these items to the deleterious effects of corrosion, chemical action and other forms of deterioration, thus posing an additional reliability problem.

Equipment should be stored under conditions which minimize rate of deterioration. This sounds very simple, but it is a fact that these conditions can only be made known by (a) accelerated ageing tests, (b) monitoring of items in storage. Accelerated ageing tests are necessary to obtain data in a relatively short time during equipment development. However, since the conditions encountered during storage cannot be perfectly simulated, they are not a completely satisfactory substitute for storage monitoring.

In order to provide data on deterioration in a form which is readily usable by (a) the agency directly concerned with the given item and (b) agencies which require such data as background information for similar items or subdivisions thereof, it is essential that such data be made available in convenient form. The most suitable forms are considered to be punch cards or magnetic tape. At present, huge masses of information are buried in miscellaneous and heterogeneous reports in the archives of multitudes of agencies. As the number of equipments in existence increases, this situation will become greatly aggravated unless a streamlined system of data reporting and reduction is adopted.

In order to provide maximum benefits from such a system, it would be advisable to retain a life history of each individual equipment from the time it is manufactured until it is removed from service by the operating unit. Only in this manner can a comprehensive knowledge of the variation in condition be obtained. The information that is obtained by the reporting sources will be transcribed to forms suitable for handling by computing machines and be subjected to statistical and engineering analyses. Results obtained will be in a form that can be used directly by designers, manufacturers, storage personnel or operating agencies.

In order that the data obtained be valid it is essential that the equipment used to test these items be of sufficient precision. Although the specifications for equipment in storage and operation are generally less stringent than those for acceptance, this should not imply that a corresponding decrease in precision of test sets used at these stages is permissible. All test sets used for any given equipment should be of similar accuracy, regardless of whether employed in the acceptance, storage or operational phases. Only in this manner, can trustworthy and comparable data be obtained.

Accuracy of measuring equipment presumes calibration against precise standards. In the interests of obtaining uniform results, it might be desirable to appoint a panel to prescribe calibrating equipment to be employed.

Another prerequisite for assuring validity of data is employment of high calibre technicians in the organizations performing the reporting function. More will be said about this problem in the next Section.

Another cause of insufficient reliability is the fact that the design of suitable test equipment is usually treated as a secondary consideration. The testers are often not available until it is much too late to be of use in assuring reliability of the item. It is necessary that design of the basic equipment and its testers be treated integrally.

8. Operation and Maintenance

Maintenance is an important factor in the effort to achieve reliability, its purpose being to sustain designed performance and continued operation of equipment and systems in order to attain the highest degree of operational readiness. Maintenance of electronic equipment is dependent upon such factors as equipment maintainability, personnel training, preventive maintenance procedures and quality of support material such as technical manuals, test equipment and test facilities.

Maintainability has already been defined in this paper as the reciprocal of the mean net time to repair failures. Unfortunately, there is nothing that maintenance personnel can do about this characteristic since it is predetermined. If the design people have been careful to observe the tenets of the disposal-at-failure maintenance philosophy such as modular construction, encapsulation, etc., then the maintainability of the equipment should be high.

Even if the design of the equipment enables relatively unskilled personnel to perform the maintenance function at the lower echelons, there is still need of highly skilled technicians at the top echelons. Unwise policies have permitted the situation to deteriorate to the point where large numbers of extremely expensive equipments are at the mercy of fewer and less skilled personnel than ever before. This grave situation can be alleviated only by taking immediate and drastic steps. The most effective one would be the decreasing of the high turn-over rate of trained men by offering sufficient incentive to remain in the services. This could be accomplished by raising the pay scales to realistic levels and by reinstituting the many fringe benefits which once were enjoyed. To assure that ability rather than longevity should be the basis for promotion, a merit system should be adopted. Another very effective means of maximizing available skilled manpower is the elimination of the practice of requiring the technician to perform non-technical routine duties. A less direct, but nevertheless important factor is the low level of technical background possessed by the average recruit, necessitating inordinately long training periods acquiring basic knowledge which should have been obtained previously. It is therefore advantageous to seek the adoption of better and more thorough training in mathematics and the physical sciences at the secondary school level.

Reliability can be greatly increased by detecting potential failures before they have an opportunity to occur. One of these maintenance techniques is marginal checking, related to the marginal checking performed during design.

The principle underlying marginal checking of electronic equipment as a preventive maintenance procedure is as follows. If all the components are in good condition, variation of parameters, generally power supply or signal voltages, will not cause the equipment to fail. However, failure may be induced if a component has deteriorated, e.g. if the transconductance has been appreciably reduced. The method employed is to vary voltages between specified limits and observe whether the equipment functions properly. For instance, in the checking of a computer, a problem may be fed to it while varying the voltage on portions of the computer in turn. An incorrect answer serves to localize the maloperating circuit and then the potentially defective part.

Another technique which is being investigated is the prediction of imminent failure based on the variation of parameters of certain electronic components. Armour Research Foundation under Air Force contract is conducting studies which indicate that resistor noise progressively increases prior to failure. It also appears that a decrease in insulation resistance of both resistors and inductors may be a harbinger of failure. Thus monitoring of the equipment may provide a means of preventing failures by furnishing sufficient warning to permit component replacement. It is suggested that research along these lines be expanded, since application of these principles will be of great assistance in improving reliability.

Support material such as test equipment, training and instruction manuals are essential for the proper performance of the maintenance function. Yet, sometimes it is found that these are not available simultaneously with the main equipment. Operation of the latter without the guidance furnished by the applicable technical manuals and use of the proper test equipment is not conducive to achievement of maximum reliability. Therefore, it is recommended that no equipment be released for distribution unless accompanied by the applicable support material.

The scope of the field covered in this paper is so tremendous, that it has only been possible to touch on the highlights. However, if the recommendations which have been made were universally adopted, it is believed that the reliability of military electronic equipment would be greatly increased.

9. Acknowledgments

The author is indebted to Mr. Robert Lusser (formerly Chief of Reliability Division, Redstone Arsenal, Huntsville, Alabama, and now Head of Research Department, Entwicklungsring Süd, Münich, Germany) for granting permission to use Fig. 2 and for reviewing this manuscript.

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An Airborne Frequency Generating Unit for the H.F. Communication Band

Presented at a Symposium on Stable Frequency Generation held in London on 25th May, 1960.

By

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J. H. GIFFORD
AND
G. E. SMYTHE †

Summary: The equipment is capable of producing an output frequency having a channel spacing of 1 kc/s in the band 3·500 to 26·499 Mc/s and a stability equal to that of a high-quality reference standard. The final output is provided by a servo-controlled variable oscillator in five sub-bands, the initial tuning being carried out by a motor-driven variable capacitor after which the oscillator is phase-locked to the desired frequency by comparison with four selectable reference frequencies generated from the 5 Mc/s standard. The control loop contains the necessary mixers, filters, phase discriminator and reactor for locking the oscillator and also the means of controlling the motor. The paper also describes the 5 Mc/s reference oscillator which employs a high quality BT cut crystal mounted *in vacuo*, operating in a fundamental series mode circuit. The use of an oven whose temperature is controlled to ~0·01 deg C permits a day-to-day stability of better than 1 part in 10^7 to be obtained.

1. Introduction

The existing congested state of the high frequency communication bands renders it increasingly important that the drives for transmitters and receivers should be derived from variable frequency oscillators having very high orders of stability, capable of being set to new frequencies very rapidly. It is also desirable that the method of communication employed should be as economical as possible of the available space and one such system is single-sideband radio telephony. The frequency generating unit which forms the subject of the present paper has been developed in conjunction with the Royal Aircraft Establishment and was initially intended as the drive unit for an existing 12-channel s.s.b. equipment, of which a self-tuning version is currently under consideration. It caters for channel frequencies from 2·000 to 24·999 Mc/s with an i.f. of 1·5 Mc/s, and the selector switching indicates channel frequency directly. A further requirement of the present unit was that it should be produced as a completely separate entity so as to preserve the maximum versatility of application. For example, in one realization it serves as a signal generator having very high orders of stability and reset accuracies; in this case the calibration is, of course, directly in output frequency.

2. Choice of System and Frequencies

2.1. *System*

While it is theoretically possible to synthesize a frequency spectrum of 23 000 channels at 1 kc/s intervals in the h.f. band directly from a number of standard decades, it is well known that this practice leads to considerable problems of filtering, with particular reference to complexity and stability, in order to achieve a high purity of output. An alternative favoured by many designers is to use one or more loops in which a variable oscillator is phase-locked to the synthesized product of the reference frequencies supplied to that loop. Such a loop often requires a servo-mechanical device for initial tuning, but since one of its properties is to oppose changes introduced into it, a high purity of output can be obtained much more simply.

It was found that the specification for the equipment under discussion could be met with filters reasonably simple to manufacture, align and maintain, by using one control loop into which the frequencies representing the megacycles and hundreds of kilocycles were introduced successively, and then providing as the signal for comparison at a phase-discriminator the sum of the frequencies representing the tens and units of kilocycles. In this way, the bandwidths of the filters could be kept sufficiently wide and the number of mixers in the loop limited, so that instability was avoided.

2.2. *Frequencies*

The overall output frequency range of the main oscillator in the control loop is, of course, settled by the specification. This has to be split up into bands for three reasons.

† Mullard Equipment Ltd., Wandsworth, London, S.W.18.

(*a*) The normal practical limitations of a variable capacitor tuned oscillator and amplifier covering 3·5 to 26·499 Mc/s.

(*b*) The need to keep any one band to less than one octave so that the oscillator cannot be tuned to a harmonic.

(*c*) The rate of tuning in degrees per megacycle should be kept as constant as possible throughout the whole range as the bandwidth of the motor control system is necessarily constant.

The lowest frequency band was therefore made to cover 3 Mc/s, and the other four bands were each made 5 Mc/s wide.

In the case of the impulse governed oscillators providing the main decades it is desirable to keep the output frequencies such that:

(*a*) The overall coverage of the stepped oscillator is less than one octave. This is, as before, to avoid direct harmonics.

(*b*) The order of the highest harmonic of the reference frequency used is less than about 100 to avoid undue difficulty in separating these harmonics from each other.

The actual frequencies used and the method of operation of all the stepped frequency generators are dealt with in more detail in later sections of the paper.

By far the greater problem in a system of this sort, however, is that of avoiding the unwanted intermodulation products due to mixing. With a range of frequencies covering nearly three octaves in the main loop, it is not possible to arrange that the intermediate frequencies shall fall between bands occupied by unwanted products in all cases, and it was therefore decided to use frequency ratios sufficiently high that all intermodulation products of lower order than the fifth fall outside the i.f. bands. This has led to the use of rather high frequencies in certain parts of the equipment, an approach to the problem which has necessitated the use of some additional stages, but which has been justified in that troubles from spurious products due to mixing have been small.

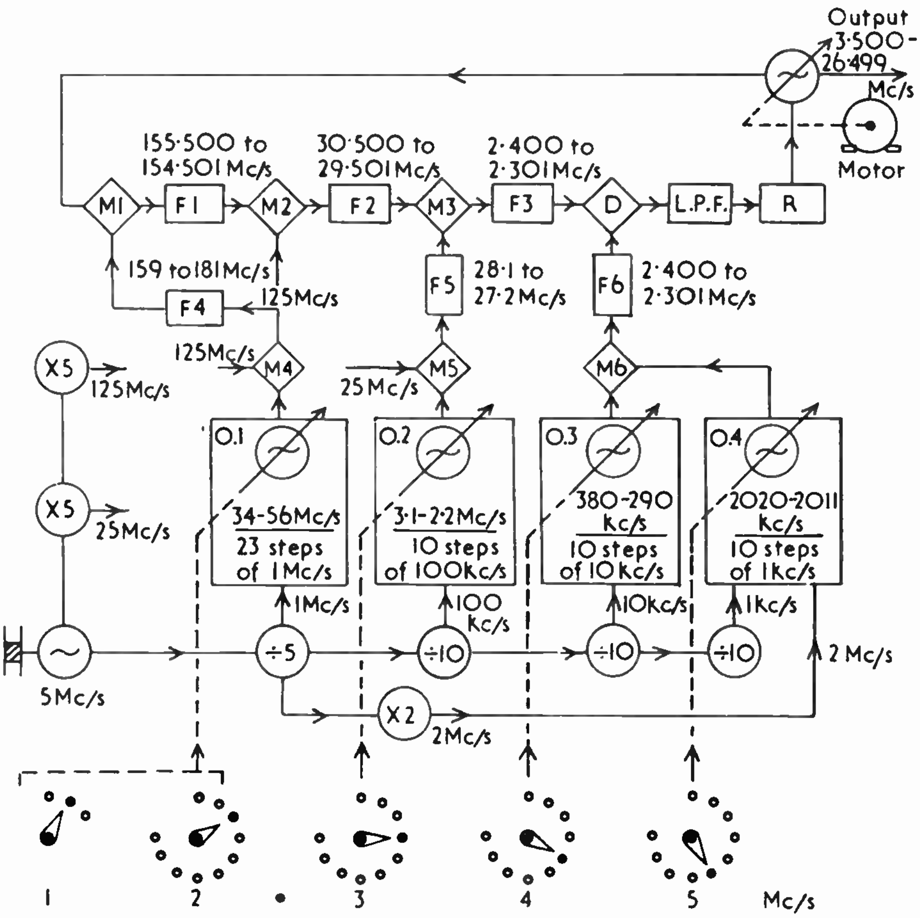

Fig. 1. Basic block diagram of system.

3. The General Circuit Arrangement

A block diagram of the system in a simplified form is shown in Fig. 1. A variable main oscillator which generates the required r.f. output is contained within a main control loop in which a portion of its output is fed via mixers M1, M2 and M3 and band-pass filters F1, F2 and F3 to a phase discriminator, D, which can provide a d.c. control signal to the reactance device, R, to maintain the oscillator in phase lock with the selected multiple of the reference standard.

By means of frequency changing in the first mixer, M1, the overall output range of 3·500 to 26·499 Mc/s is divided up into 23 bands each 1 Mc/s wide by providing 23 spot frequencies at discrete 1 Mc/s intervals from 159 to 181 Mc/s inclusive, so that for each 1 Mc/s band of the oscillator coverage one, and only one, of these frequencies can produce the first i.f. band of 155·500 to 154·501 Mc/s in the filter, Fl. For example, the difference between 159 Mc/s and the output frequency band of 3·500 to 4·499 Mc/s gives this i.f. band, while 160 Mc/s combines with 4·500 to 5·499 Mc/s to give the same result, and so on. Thus there is a direct relation between the spot-frequency introduced into M1 and the megacycle band of the output frequency in use.

These 1 Mc/s step frequencies are obtained by mixing in the mixer, M4, a fixed 125 Mc/s signal with the output of a generator, O1, and selecting the sum of these frequencies in the filter, F4. The generator, O1, is an impulse governed oscillator (i.g.o.) which produces the 23 harmonics of 1 Mc/s from 34 to 56 Mc/s inclusive, phase-locked to the 5 Mc/s standard. These frequencies can be selected by the two switches corresponding to the tens and units digits of the required channel frequency in Mc/s. This first i.f. band of 155·500 to 154·501 Mc/s is now moved to a second i.f. of 30·500 to 29·501 Mc/s by selecting its difference with 125 Mc/s in filter, F2, after frequency changing in mixer, M2.

By a similar process to that employed in mixer, M1, the band of 30·500 to 29·501 Mc/s is now further subdivided into 10 bands of 100 kc/s bandwidth each. This time, 10 spot-frequencies at discrete 100 kc/s intervals from 28·1 to 27·2 Mc/s inclusive are provided. It can now be seen that the third i.f. band of 2·400 to 2·301 Mc/s will be produced in the filter, F3, with a spot frequency input to M3 of 28·1 Mc/s by a signal going from 30·500 to 30·401 Mc/s; similarly a spot frequency input of 28·0 Mc/s will select the band 30·400 to 30·301 Mc/s, and so on. There is, therefore, a direct relation between the spot-frequency applied to M3 and the 100 kc/s band of the output frequency in use.

The 100 kc/s step frequencies are obtained in the filter F5, as the sum of a fixed 25 Mc/s and the output of a generator O2, after mixing in a mixer, M5. The generator, O2 is a second impulse governed oscillator providing ten harmonics of 100 kc/s from 3·1 to 2·2 Mc/s inclusive, phase-locked to the 5 Mc/s standard. These frequencies can be selected by the ten-position switch corresponding to the tenths digit of the required channel frequency in megacycles.

The signal from filter, F3, is now fed into the phase-discriminator, D, whose other input consists of 100 spot-frequencies at 1 kc/s intervals in an identical band of 2·400 to 2·301 Mc/s. These spot frequencies are obtained by the direct addition of the outputs of the generators, O3 and O4, in the mixer/filter arrangement M6/F6, the frequencies required being selected by the fourth and fifth of the 10-position switches indicated at the foot of Fig. 1.

The generator O3 is a third impulse governed oscillator producing ten harmonics of 10 kc/s from 380 to 290 kc/s inclusive, while O4 makes use of a drift-cancelling sidestep technique to produce 10 harmonics of 1 kc/s from 2020 to 2011 kc/s. These generators also are driven by reference signals derived from the 5 Mc/s crystal standard, as are the fixed frequencies previously mentioned.

To set up the system on a particular frequency therefore involves selecting the corresponding output from each of the four generators O1 to O4 by setting up the five switches to the required numbers as described above. When the channel has been selected, the variable oscillator must then be tuned to within a few kilocycles of the correct frequency when, by the process described, the main loop signal arriving at the discriminator D will be near enough to the reference signal obtained from O3 and O4 for the reactor to lock the oscillator exactly to the frequency required. In practice, this is achieved automatically: the main oscillator is tuned by a motor in such a way that the frequency increases with forward rotation. The means of controlling the motor has been omitted from the block diagram (Fig. 1) for clarity but is described in more detail later in the paper. It is, however, necessary to describe the mode of operation briefly at this stage.

In order to ensure that channel changing shall be accomplished within about 5 seconds, the speed of the motor has been made variable by means of a transistor circuit. If the oscillator frequency is far from the required frequency, the tuning sequence is then as follows:

(*a*) The motor runs at full speed until the output frequency is about 200 or 300 kc/s away from the desired point, and then:

(*b*) The motor speed is reduced rapidly to a constant slow speed. The motor, however, cannot stop until:

(*c*) The frequency is within about 3 kc/s of the required point, whereupon the motor is stopped and the reactance device captures and locks.

(*d*) The control of the motor (slow forward or reverse) is then handed over to the reactor valve current so that the system can be maintained in lock.

The tuning capacitor is capable of 360 deg rotation, but 180 deg of this is made inoperative by a cam-operated microswitch so that the frequency always increases with forward rotation. The required setting is always reached by the capacitor being driven in this forward direction.

4. Details of Equipment

4.1. *The Mixer and Filter Assembly*

This module contains all the mixers in the main control loop (M1 to M3 inclusive), and also the mixers M4 and M5 together with their associated filters. Its output feeds the main loop signal to the module containing the phase discriminator D.

Several types of mixer circuit are used, employing sub-miniature pentodes type 5636 and 5840. The former, having a short base suppressor grid characteristic, permits separate injection on g_1 and g_3, while both signals can be fed to g_1 of the 5840 through a suitable network. A balanced mixer with a pair of 5840's is used at M5 where a leak of 25 Mc/s reaching M3 along with the required signal could result in demodulation and so cause a spurious signal in the main loop amplifier, particularly on the 7th and 8th steps of O2 (namely 2·4 and 2·3 Mc/s). So that the output circuit F5 can be single-ended, both inputs to M5 are injected in push-pull, the high level (25 Mc/s) to g_1, the low level to the cathodes, and shunt acceptor circuits tuned to 25 Mc/s to make the carrier balance less critical are included in filter, F5.

The filters used are mainly of the mutual inductance coupled bandpass type. The chief exception to this is in the u.h.f. filter, F4, where owing to the high frequency and wide bandwidth it was found that the use of top capacitance coupling resulted in less interdependence between the tuning and coupling adjustments. For this purpose a special miniature trimmer having negligible stray capacitance from either electrode to earth was developed.

In some of the stages shown in Fig. 1, the output from one mixer has to be fed to the next mixer as the high level input. In these cases, an amplifier stage is incorporated as part of the filter where necessary, but these have not been shown on the diagram in the interests of clarity.

4.2. *Impulse Governed Oscillator Assemblies* O1, O2 *and* O3

From the discussion in Section 3 it can be seen that any desired output frequency involves the production in the unit of four selectable reference frequencies, the first in the range 34 to 56 Mc/s, the second in the range 3·1 to 2·2 Mc/s, the third in the range 380 to 290 kc/s and the fourth in the range 2020 to 2011 kc/s. For the three first mentioned use is made of a technique of synchronizing an oscillator to the appropriate harmonic of a reference frequency converted to a pulse sufficiently short to include harmonics up to the highest required, (i.g.o. technique).[1] For example, the first reference oscillator, shown as O1 on Fig. 1, has output frequencies of 34, 35, 36, etc. to 56 Mc/s and is therefore supplied with a reference frequency of 1 Mc/s; similarly O2 will require 100 kc/s and O3 10 kc/s.

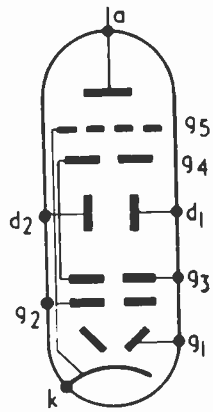

Fig. 2. The beam deflection tube, type E80T.

The two functions of pulse generation and discrimination are conveniently combined in the beam deflection tube E80T illustrated in Fig. 2. In this the reference frequency, applied to plates d_1 and d_2, generates the short pulses by sweeping the electron beam across the slot in g_4, while the discriminator action results from the modulation of the electron beam by the signal to be synchronized, applied to g_1. Since the short pulses exist only in the E80T tube there is a major advantage in isolating them from the rest of the circuitry. In the anode circuit they are integrated and form the d.c. control signal fed to the reactance device controlling the oscillator. In investigating the performance of such a loop, square-wave, transient disturbances of the oscillator frequency were produced and the response of the system could be clearly seen on an oscilloscope connected to observe this d.c. control signal. The display showed the characteristic highly damped oscillation of a servo loop and indicated that the effective bandwidth was approximately that of the filters in the signal path round the loop.

The block diagram of Fig. 3 shows a complete i.g.o. unit. The sweep voltage is derived by division of the

5 Mc/s standard oscillator. The oscillator to be controlled is set by its normal tuning device (e.g. switched preset capacitors) to *n* times the sweep frequency and provided with a reactance control device which accepts the slowly varying d.c. from integrated anode pulses as its input, thus completing the control loop, since any change in the relative phase of the controlled oscillator and the sweep voltage will cause a variation in the input to the reactance device in such a sense as to oppose this phase change. The oscillator is thus locked to the sweep voltage frequency. It is a feature of most such circuits that the capture range is much less than the holding range making it necessary to provide a means of swinging the oscillator frequency over a small deviation to ensure that it comes within the capture range of the device.

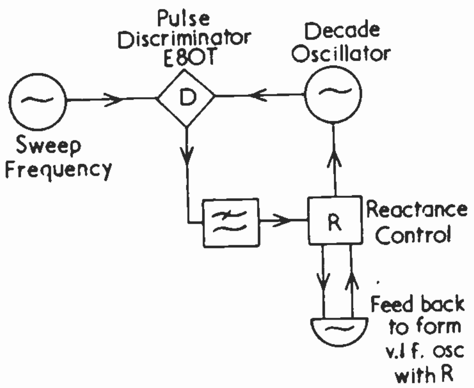

Fig. 3. Impulse governed oscillator (i.g.o.).

This is done by making the d.c. control valve form part of two loops, one as above described and having a high loop gain in the interests of close control, while the second forms part of a v.l.f. oscillator having lower loop gain. When the system is not in phase lock this latter loop causes the d.c. control valve to oscillate at about 5 c/s, thereby swinging the oscillator frequency at the same rate so that in some part of this excursion the oscillator frequency will be the necessary integral multiple of the sweep frequency; upon this happening the main control loop locks the oscillator to the sweep frequency, its higher loop gain stopping the v.l.f. oscillation of the d.c. control valve.

The same basic principles underlie all three i.g.o. units, each having a similar Colpitts oscillator in which the preset tuning capacitors for each of the required output frequencies are selected by electro-magnetically actuated switches. This makes it possible for the setting of the required channel frequency in the form of digital switching to be translated into the actual frequencies required to achieve this result, taking account, in addition, of the i.f. of 1·5 Mc/s when the equipment is used with the s.s.b. apparatus.

4.3. *The Sidestep Oscillator* O4

Whilst it is possible to use the i.g.o. technique to produce 1 kc/s steps it has been found undesirable due to susceptibility to microphony. The bandwidth of the control loop must, of course, be substantially lower than the step interval, in practice of the order of 100 c/s. This means that it is unable to correct for transients having frequencies greater than this. Microphony in valves or other transients due to vibration can occur with frequencies approaching 1000 c/s, and can either cause noise modulation or, in the extreme, unlock the control loop.

For this reason it was decided to use the sidestep technique. In this method a group of ten auxiliary crystals is used as a means of selecting the appropriate harmonic of a 1 kc/s spectrum. The frequency stability of these crystals is required merely to be adequate to make this selection (performed by a mechanical filter) unambiguous but does not appear in the final output of the f.g.u., as will be seen from consideration of Fig. 4.

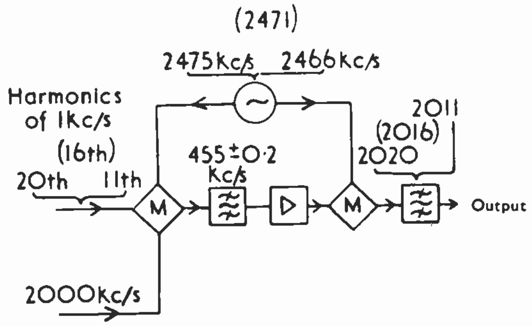

Fig. 4. Sidestep oscillator.

The first mixer has applied to it a signal at 2·000 Mc/s and a pulse at 1 kc/s both of these being derived from the 5 Mc/s primary standard; these mix to produce a spectrum of frequencies spaced 1 kc/s apart, those of interest being 2020 to 2011 kc/s. In order to select from the latter the signal corresponding to the desired final digit in the f.g.u. output, for example 2016 kc/s (corresponding to a 4 in this position), the mixer has a third input from the auxiliary crystal oscillator on a frequency chosen to give 455 kc/s when mixed with the appropriate signal in the range 2020 to 2011 kc/s (2016 kc/s will require 2471 kc/s). This will be accepted by the mechanical filter which has a bandwidth limited to 0·2 kc/s on either side of its nominal frequency of 455 kc/s. The signal is amplified and mixed in a second mixing stage with the original 2471 kc/s to yield 2016 kc/s as required, this is effectively the sum of 2000 and 16 kc/s both of which have the stability of the 5 Mc/s standard while the

2471 kc/s having been successively put in and taken out of the mixing process, does not affect the result. From this it can be seen that the requirement for the ten auxiliary crystals is that their tolerances and drifts, together with the tolerance and drift on the mechanical filter, shall not cause the nominal 455 kc/s signal from the first mixer to fall outside the pass-band of the mechanical filter; this is a result that can be achieved without recourse to ovens for either crystals or mechanical filter.

Finally, the output from the side-step oscillator is mixed with that from O3 to produce a frequency lying between 2301 kc/s and 2400 kc/s which is applied to the phase discriminator of the main loop (D in Fig. 1) where it is compared with the main loop signal.

4.4. *The 5 Mc/s Standard Oscillator*

Since, as has been shown, the accuracy of the final output frequency depends only on the 5 Mc/s standard it is necessary to make this of the highest possible stability compatible with the limitations of airborne apparatus.

While the extremely stable performance available from the fifth overtone mode series type oscillator[2] was attractive, adequate stability was obtainable from a simpler circuit, basically a Colpitts oscillator with automatic level control developed in conjunction with the crystal manufacturers whose special 5 Mc/s fundamental series mode quartz unit is employed in this equipment. This has the additional advantage of a higher permissible drive level allowing the required output voltage to be achieved with fewer stages. The crystal is enclosed in a cylindrical oven block of anodized aluminium which has the heating elements wound directly on its surface, the anodic film providing the requisite electrical insulation with good heat conductivity. The thermal insulation is provided by layers of glass wool and aluminium foil, with an outer jacket of expanded polythene. Heat losses from the ends of the oven block are met by the use of lead-out wire preheating elements and by decreasing the heater winding pitch towards the ends.

To meet the specified requirements, the temperature of the oven block is raised rapidly from cold by a coarse heater which is switched off at about 62°C by a small bimetallic thermostat; thereafter the control of temperature is effected by a fine heat element controlled by a special mercury capillary contact thermometer which incorporates a heater winding in order to make the cycling time very short. By this means the temperature in the crystal space is held to within 0·01 deg C, near 75°C, the cycling time being about 3 seconds "on" and 7 seconds "off" at room ambient. The reduction factor of this oven is better than 250, even better results having been obtained with certain experimental versions and the frequency stability of the ovened crystal with its associated oscillator circuit comfortably exceeds the target of 1×10^{-6} over six months in its working range of −40°C to +55°C. The 1 Mc/s signal required for synchronizing O1 is produced from the 5 Mc/s output by division in a 5:1 regenerative divider while the 100 kc/s, 10 kc/s, and 1 kc/s serving O2, O3 and the sidestep oscillator O4 are produced by successive division of the 1 Mc/s signal in 10:1 dividers. Their outputs are sinusoidal except in the case of the 1 kc/s divider which produces 15 V positive-going pulses for the sidestep oscillator.

4.5. *The Discriminator Unit*

As has been seen, the operation of the system is such that the comparison of the signal from the variable main oscillator and the signal from mixer No. 3 is made always between the frequencies of 2301 and 2400 kc/s inclusive and three pieces of information are extracted from the discriminator unit D in Fig. 5, for the purpose of controlling the variable oscillator.

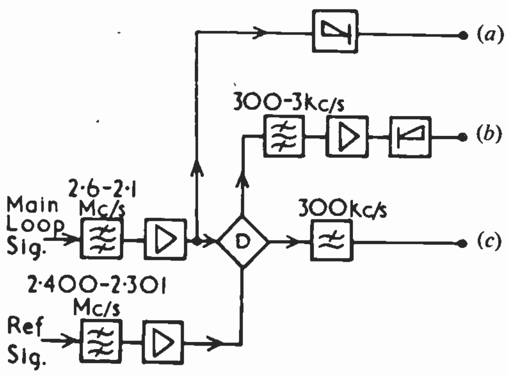

Fig. 5. Main loop discriminator.

These three signals are:

(*a*) that the main loop signal frequency is approaching the desired setting,

(*b*) that the main loop signal frequency is now within the capture range of the main oscillator reactance device,

(*c*) the control signal which maintains the loop in lock.

The first of these signals is readily derived by simple rectification of a portion of the output of the amplifier supplying the frequency generated from the variable oscillator to the discriminator, since when there is output from the bandpass filter in this chain requirement (*a*) is met. At this point the two signals will be giving rise to a beat in the discriminator and the beat will become zero when they coincide in frequency; this fact is used to produce the second signal. Since the reactance device can capture the variable oscillator as soon as it gets within about 3 kc/s of the reference (in the worst case) the amplifier handling this beat signal has a response which reduces the beat output effectively to zero below about 3 kc/s. Since, however, it is a condition of the system logic that signals (*a*) and (*b*) must initially appear together, the high frequency response of this amplifier must be maintained to about 300 kc/s. The signal (*c*) of Fig. 5 is produced by a normal phase discriminator. After integration, the resulting d.c. output of this circuit is passed to the control grid of the reactance device of the variable main oscillator.

4.6. *Variable Main Oscillator and Motor Control Assembly*

The variable main oscillator, which provides the output from the equipment, is ganged to an amplifier, the tuning capacitors being driven by a small motor via a 600 : 1 gearhead. The variable capacitor consists of two unequal sections in each gang which makes possible a more linear coverage of the total range in five bands, one covering 3·5 to 6·499 and the remainder covering each a 4·999 Mc/s band up to 26·499 Mc/s. An a.g.c. system is fitted to the amplifier to hold the output constant at about 5 V into 150 ohms. When the motor has rotated the gang capacitor into the required position the oscillator is phase-locked to the reference frequency by a reactance valve.

In an earlier equipment the control of the motor was effected by means of relays and a mechanical change speed gearbox as in Camfield's system[3] but in later versions the relays have been replaced by transistor circuits. The requirements of the system are:

(1) In the absence of the correct signal the motor should run forward.

(2) The motor should have two speeds, a high speed and a constant slow speed.

(3) When within the capture range of the reactance valve of the oscillator the control of the motor should be derived from the reactance valve cathode current. When this current is near its mid-range no action is required from the motor; should the current approach either upper or lower limit the motor must move in such a direction as to restore the reactance valve current to mid-range. In the present system this calls for forward rotation when the current goes high and reverse rotation when it goes low.

In the system the direction of rotation is controlled by a pair of bistable circuits operating at different levels and having a degree of backlash, permitting one to be triggered "on" with low reactance valve current (remaining "on" till the current returns to mid-range value), while the other triggers "on" when the reactance valve current goes to its upper limit, similarly remaining on until the current returns to mid-range. From this it can be seen that neither will be on if the current does not vary beyond either upper or lower limits and thus the motor will be stationary. This control of the direction of rotation is overridden by the output of an AND gate having inputs from the near-frequency and on-frequency circuits so that the motor is constrained to run forward until the correct response is received from both these circuits.

The near-frequency signal is derived from a filter having a wide bandwidth such that sufficient output is delivered from it when the signal has approached within about 200 kc/s of the required setting. In addition to feeding the AND gate this output controls the motor speed; in its absence the motor runs fast. The on-frequency signal is the output of the beat detector and the condition which trips the AND gate is the null output when the beat frequency falls to zero.

The control of the motor speed is effected by having the armature of the permanent magnet field motor in the emitter circuit of a compound emitter follower, the armature voltage is thus the potential to which the input base is set up by the near-frequency signal (a clamp is provided to determine the minimum speed to prevent this circuit from actually stopping the motor). Means are also provided in the circuit design to make this minimum speed independent of changes in supply voltage and in load on the motor shaft over a considerable range of variation.

The system cannot, however, remain stationary or give the appearance of being in lock when it is in an unlocked condition. A transient sending the reactance valve current downwards will switch the motor into reverse. While this will move the capacitor of the oscillator away from the correct setting it will, however, recover by its normal action of going forward if the AND gate is tripped. Transients sending the reactance valve current high will switch the motor forward and from this it can only recover by making a complete 360 deg rotation.

5. The Physical Arrangement of the F.G.U.

The complete system is designed to fit a standard aircraft rack and its dimensions are 13 in. wide by 8 in. high by 13 in. deep. The circuitry is divided into eight modules and a supporting rack which carries the interwiring and sockets for the modules (Fig. 6). One of the modules contains a printed circuit board which provides the 60 separate switches required in order to provide pre-selection of 12 channels each of five digits. This multiple switch panel is on the front face of the equipment, covered by a lid, and its supporting frame carries also a switched meter which enables the performance of various key points in the system to be monitored. To contain the remaining seven units the supporting framework is constructed

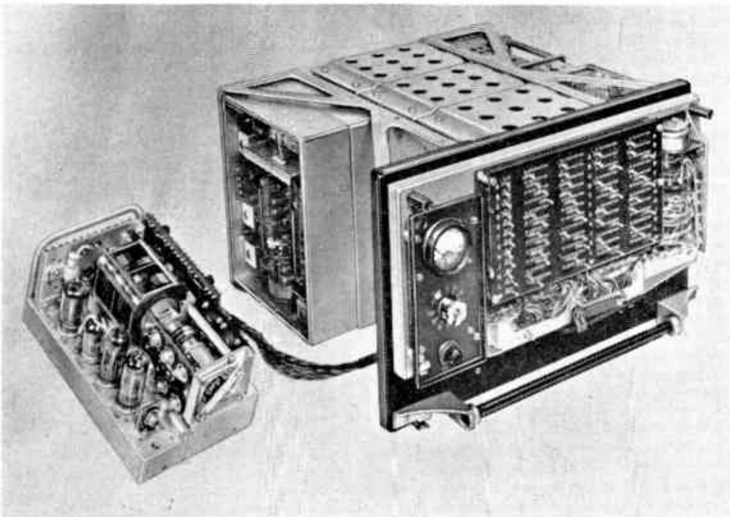

Fig. 6. The airborne frequency generating unit with covers removed showing the twelve-channel frequency preselection panel and the main oscillator extracted on test lead to illustrate sub-unit construction.

with two vertical members forming a central well into which the three i.g.o. reference oscillators O1, O2 and O3, are plugged vertically downwards; the outside of the well carries the 5 Mc/s standard oscillator and mixer/filter unit on one side with the variable main oscillator and sidestep oscillator O4 with discriminator unit on the other. This form of construction provides a very strong and compact assembly with adequate freedom of passage for cooling air forced in by a blower mounted on the aircraft racking at the rear of the f.g.u.

All switching operations involved in setting up a frequency are performed by electro-magnetically-actuated switches and the input information can be provided either by a control box having manually operated digital switching (used with self-tuning transmitter/receiver equipment) or from a control box having a channel selector switch connected to a switch which selects the information stored by the group of switches relevant to that channel on the printed circuit multiple switch unit (used when the driven equipment operates on preset channels only). In addition, the f.g.u. makes available externally the band-switching information used in its own variable main oscillator.

6. Acknowledgments

In conclusion the authors wish to acknowledge the assistance given by the other members of the f.g.u. team, Messrs. A. Klimek, J. Payne, and J. Tozer, by whom a great part of the development work on the present device has been carried out, likewise the co-operation and guidance of Mr. G. W. Barnes and his colleagues at the Royal Aircraft Establishment. Thanks are also due to the Directors of Mullard Equipment Ltd. for permission to publish this paper.

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8. Appendix

The actual relation between the output frequency f_0 Mc/s, and the frequencies a, b, c and d Mc/s of the four generators O1 to O4 respectively is as follows:

Mixer M1 has inputs of $(a+125)$ Mc/s and f_0 Mc/s, and the first i.f. is therefore $(a+125-f_0)$ Mc/s. After subtracting 125 Mc/s in M2, the second i.f. is given by $(a-f_0)$ Mc/s which is then passed to M3 where a frequency of $(b+25)$ Mc/s is subtracted from it. The loop signal arriving at the phase discriminator D is therefore represented as

$$[(a-f_0-(b+25)] \text{ Mc/s.}$$

This has to be made equal to the sum of c and d Mc/s, so therefore

$$a-f_0 - (b+25) = c+d$$

therefore $f_0 = a-b-c-d - 25$ Mc/s.

In the example shown at the foot of Fig. 1, an emitted frequency of 12·345 Mc/s has been selected. This means that $f_0 = 12{\cdot}345+1{\cdot}5 = 13{\cdot}845$ Mc/s.

Now: $a = 44$ Mc/s, $b = 2{\cdot}8$ Mc/s, $c = 0{\cdot}34$ Mc/s, $d = 2{\cdot}015$ Mc/s.

$$\text{Therefore } f_0 = 44-25-(2{\cdot}8+0{\cdot}34+2{\cdot}015) = 13{\cdot}845 \text{ Mc/s.}$$

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The Change-of-State Crystal Oven

Presented at a Symposium on Stable Frequency Generation held in London on 25th May 1960.

By

D. J. FEWINGS, B.Sc.†

Summary: A description is given of a new high precision crystal oven which depends for its action upon the natural stability of the melting point of a pure crystalline material and upon the thermal ballasting which the property of latent heat of fusion provides. The necessity for complicated controlling circuitry is avoided, the power to the oven being controlled simply by means of a micro-switch. The underlying principles are explained, and constructional details given with a brief account of development problems and their solution. A summary of the results obtained is given: a change of 10 deg C in ambient temperature causes a frequency shift of 2·8 parts in 10^8.

1. Introduction

The process of frequency synthesis is of necessity complicated, involving a multiplicity of divider circuits harmonic generation and separation circuits and, in some designs, oscillator locking circuits. Such complication is unavoidable if the highest stability is to be achieved. At the heart of every synthesizer is a stable oscillator which governs the stability of every frequency generated in the equipment. This oscillator generally derives its stability from a quartz crystal maintained at a constant temperature in some form of oven. The temperature controlling mechanism of the oven tends to be complicated and the oven itself large when very high stabilities are aimed at. The change-of-state oven does at least offer a simplification to this part of a synthesizer since it can be relatively small and is self-controlling.

The usual methods of thermostat control such as the bi-metal contact breaker, the contact thermometer or the temperature sensitive bridge with its ancillary phase-sensitive amplifier and relay, produce an oven temperature which fluctuates continuously above and below the desired temperature. Even if proportional control is employed there must still be a temperature differential since a temperature error must occur before it can be corrected. The variation can of course be made negligibly small if the oven is made sufficiently massive and if the error correcting voltage is sufficiently amplified. In the change-of-state oven to be described correction of this type of error does not arise and consequently no special circuitry is required.

The degree of accuracy required of a synthesizer is a matter of some controversy but for nearly all applications a day-to-day stability of 1 part in 10^7, and six-months stability of 5 parts in 10^7 is probably good enough. The change-of-state oven can achieve this order of stability comfortably.

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2. General Principle

One of the most constant things in nature is the melting temperature of a pure crystalline substance. Extremes of pressure can alter it but provided that extreme pressure changes are avoided, the melting point of such a substance can be relied upon as a temperature standard (e.g. 0°C for melting ice). Another advantage which can be gained by the use of a melting point as a temperature standard derives from the property known as the latent heat of fusion. This can be defined as the heat which is required to convert the substance from the solid to the liquid state without changing the temperature. This property

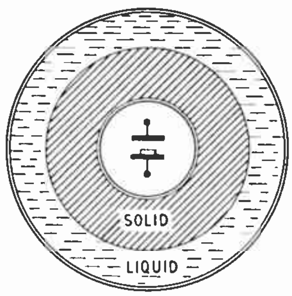

Fig. 1. The ideal oven.

leads to the valuable result that when the substance is partly melted, any additional heat which is applied is absorbed in causing more of the material to melt while the temperature of the mixture remains unchanged at the melting point. If we imagine an enclosure embedded in the middle of a sphere of some crystalline substance (Fig. 1), then, if heat is applied uniformly to the outside of the sphere until a layer of the material is melted, we know that at the boundary between the solid and liquid phases the temperature must be at the melting point of the substance used. The enclosure is thus entirely surrounded by an isothermal layer and since there can be no heat losses in this hypothetical arrangement, the temperature of the enclosure must rise until it too is at the melting point temperature and will remain so as long as the conditions are maintained. If more heat is applied then more of the substance will melt and the diameter of the solid sphere will diminish but the temperature of the boundary layer cannot alter. Such an arrangement would make a perfect crystal oven, unaffected either by ambient temperature changes or by thermostat differential. In any practical oven the crystal enclosure must of course be supported mechanically and leads must be brought out from the crystal. Both of these practical requirements provide paths down which heat can be lost and the degree of perfection which is achieved in making an oven using the above principles depends upon keeping these losses to a minimum. This limitation applies of course to any type of oven, whatever the type of temperature control employed.

3. Practical Design

In a practical design, means have to be found to maintain a fixed portion of the crystalline filler in the melted condition. The simplest solution is to employ a substance which expands substantially on melting and to use this property to cause the heat supplied to the oven to be switched off when a certain fixed volume has been reached. This is conveniently achieved by using a container fitted with an expansible bellows operating a micro-switch. A convenient filling material is naphthalene which melts at 79·5° C and expands rather more than 10% in volume in melting. It melts without decomposition and does not attack metals.

In early experiments considerable difficulty was encountered in using the bellows and micro-switch technique. It was found that so long as the oven was allowed to run uninterruptedly it worked well. When, however, it was allowed to cool repeatedly, trouble would soon develop. The cause was simply that, upon switching off, the bellows, being of light metallic construction, would cool more rapidly than the rest of the oven and would freeze solid while some of the filler in the remainder of the oven was still liquid. On complete solidification, a vacuum space would be left which would fill with air previously held in solution. This fault was progressive, the bellows would freeze closer and closer to the micro-switch on each heating and cooling cycle. Finally the bellows would freeze so close to the micro-switch that upon switching on again, the first movement of the bellows would operate the switch and the bellows would then freeze with the oven in the off condition.

It was clear from these failures that it was essential to prevent the too rapid cooling of the bellows end of the oven. Calculations were made of the average thermal capacity per unit length of the oven remote from the bellows. The bellows were then enclosed in a separate brass chamber perforated at the end to admit the filler and of dimensions calculated to produce a thermal capacity per unit length equal to the average for the rest of the oven. This ensured that if heat losses were uniform the whole oven would cool at the same rate. In a practical design to be described however, heat losses are slightly greater at the end remote from the bellows which is thus the first part of the oven to cool. Thus the major design difficulty was eliminated.

Figure 2 shows a sectional view of a change-of-state oven. In this diagram A is a brass cylindrical chamber which houses the crystal. It is closed at one end and is mounted on and soldered to a ceramic cylinder B. The other end of the ceramic cylinder is soldered to a brass end plate C. A copper tube D is passed through and soldered into C and is used for filling the oven. Soldered to C is the outer cylinder of the oven F upon which is wound a heater winding G.

At the other end of the oven is a metallic bellows H soldered to a brass member J which in turn is soldered to the bellows chamber K. This chamber is soldered to and forms an extension to the cylinder F, the heater winding being continued over its outer surface. The inner end of the bellows chamber has a number of holes drilled in it to enable the filler to penetrate. Within the bellows space is mounted the micro-switch assembly. The micro-switch L is sandwiched between two tufnol blocks M. Holes through these blocks enable them to be mounted on two screws N which screw into pillars O. The micro-switch can slide along the screws and is spring-loaded against their heads. The pillars O are soldered into two ceramic bushes which are in turn soldered into a brass member Q which screws into a thread cut in the member J. Connections to the micro-switch are taken to the pillars O, the ends of which protrude beyond the ends of the ceramic bushes and enable connections to be made to the heater winding and power supply. A small hole in the member Q prevents a build up of air pressure within the bellows.

3.1. *Micro-switch Setting*

Initially, the micro-switch operating plunger is positioned clear of the bellows by a distance which determines the desired proportion of melted to unmelted filler. Ideally the heating power should be removed when the layer of solid covering the crystal compartment is as thin as possible consistent with its being continuous over the whole surface. This is because since we know that some heat will be lost down the crystal wires and the crystal chamber support, there will inevitably be a small temperature gradient across the thickness of the solid layer of the filler and the thinner it is made the smaller will be this gradient. Such a gradient is harmful because it will vary with the heat losses which in turn will vary with the ambient temperature. In practice it is satisfactory, in the design illustrated, to set the micro-switch about $\frac{3}{16}$ in. clear of the bellows in the cold condition.

The spring loading of the micro-switch assembly enables a possible initial overshoot to be accommodated without damage to the micro-switch. Also, if for any reason the micro-switch should fail to switch off when operated, continued expansion of the filler can press back the micro-switch against the spring loading until the bellows touches one of the screws N. Since the power to the oven is supplied via these screws, contact with the earthy bellows puts a short circuit across the supply and blows a fuse thereby preventing damage.

press against the inner surface of the crystal chamber and convey heat from the oven to the base. The flying leads from the crystal are taken through small insulated holes in the base and through the block S to the points W. From the points W to the appropriate pins on the octal base plug are taken thin (38 S.W.G.) eureka wires. The heat supplied to the crystal base reduces the temperature gradient between the crystal and its lead-out wires and this reduces the heat lost by the crystal down these leads. The thin eureka wires also serve to reduce heat losses.

The base T carries three grub-screw terminations to which the heater and micro-switch leads are taken. The oven cover is also fixed to T and the space between the cover and the oven is filled with felt Y.

3.3. *Assembly*

The assembly of the oven is simplified by the use of two solders which have differing melting points. The chamber A is soldered to the ceramic tube with soft solder (m.p. 170° C) and B is soldered to the

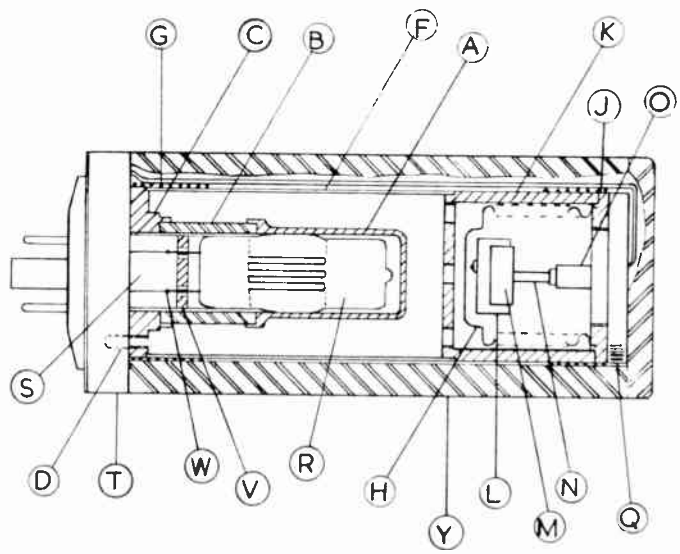

Fig. 2. Construction of practical oven.

3.2. *Crystal Holder*

Referring again to Fig. 2, the crystal and crystal holder can be seen inserted into the oven. R is the crystal mounted on a heat insulating block S which in turn is mounted on a tufnol base T. Attached to T is a bakelite octal plug to which all the connections to the oven and to the crystal are made. V is a guard ring whose function is to reduce heat losses down the crystal leads. It comprises a brass base supporting a cylinder of phosphor-bronze within which the crystal is seated on a felt pad. The part of the cylinder remote from the base is split into a number of fingers which

member C with a higher melting point solder (290° C). This enables the joint to be made between the members C and F with the lower melting point solder without disturbing the joint between C and B. Similarly, the bellows is soldered to member J with high melting point solder and the joints between J and K and between K and F with low melting point solder.

3.4. *Filling*

Clearly, filling the oven has to be done with the filler in the liquid state. When cold, however, the oven must be completely filled with the solid substance and since solidification produces a reduction in volume in excess of 10%, a special technique has to be adopted in filling.

The crystal oven is supported with its filling tube uppermost and a funnel is attached to the filler tube by means of a rubber tube which is rigid enough for the funnel to be self-supporting. An oven is lowered over the assembly and the temperature raised to about 90°C. Liquid naphthalene is then poured into the funnel and air is forced out of the assembly by agitating the bellows. When all the air has been removed and the oven is full of the liquid, a head of liquid naphthalene is left in the funnel. The external oven is then raised so that it is only heating the upper half of the crystal oven and a cooling fin is clamped to the bellows chamber. This allows the crystal oven to cool from the bottom upwards. Crystallization of the filler thus commences at the bottom and proceeds upwards drawing more liquid naphthalene into the oven from the funnel as contraction takes place. Having established the temperature gradient, the external oven is raised until only the funnel and connecting tube is heated and cooling is allowed to proceed to completion. The funnel is then removed and the connecting tube cut off to about $\frac{3}{8}$ in. long, cleaned out, crimped and soldered.

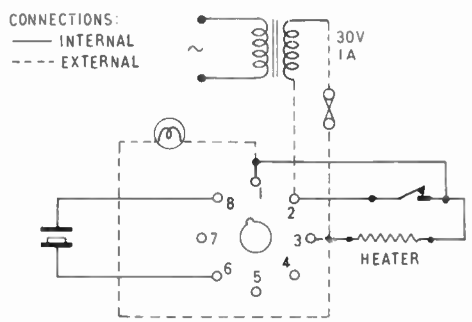

Fig. 3. Power supply connections.

3.5. *Circuit Details*

Figure 3 shows the connections to the power supply, micro-switch and indicator lamp.

Figure 4 shows the circuit diagram of the crystal oscillator used. The oscillator is a Colpitts type with an amplifier providing a feedback voltage which reduces the voltage across the crystal to a low level (< 200 mV) and also feeds a low impedance output stage. A neon stabilizer valve keeps the h.t. voltage sensibly constant at 150 V.

3.6. *Oven Temperature Control*

The operating temperature of a change-of-state oven is determined by the melting point of the filler. If a change of temperature is required it is necessary to choose a new filling material. For instance, a successful oven has been made using benzophenone as the filler, the temperature being 48° C.

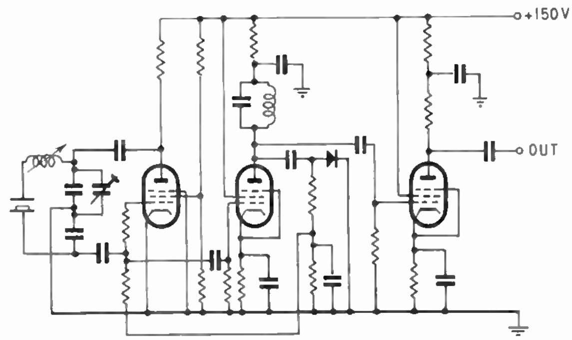

Fig. 4. Circuit of the complete stable oscillator.

It is sometimes desirable when extreme accuracy is required, to match the oven temperature to the temperature of zero temperature coefficient of a particular crystal. Crystals can be cut commercially so that their point of zero temperature coefficient is determined to within ± 3 deg C of a desired temperature. This tolerance can be partially accommodated with a naphthalene filled oven by making use of the depression of the melting point which occurs when an impurity is present. By adding up to 10% by weight of anthracene to the naphthalene it is possible to vary the melting point of the mixture from 79·5° C to 76·4° C. Figure 5 shows how the melting point of naphthalene varies with the admixture of various percentage weights of anthracene.

For normal use within the frequency tolerances stated earlier, this precise matching of crystal to oven is not necessary as the performance figures demonstrate.

3.7. *Practical Details*

Figure 6 shows a photograph of a completely-assembled oven together with a crystal holder and crystal. The dimensions of the oven are 6 in. × $2\frac{1}{2}$ in.

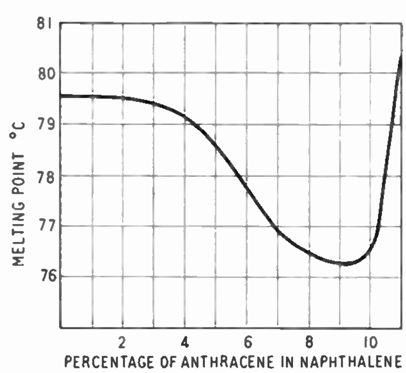

Fig. 5. Depression of melting point of naphthalene by an impurity (anthracene).

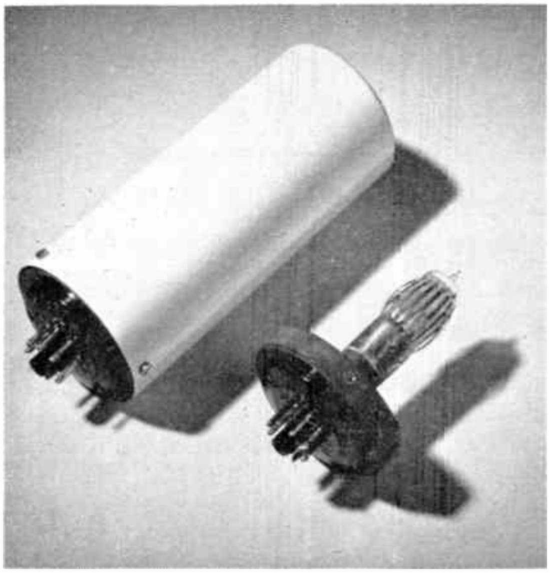

Fig. 6. The oven and crystal holder with crystal.

(dia.). The only external apparatus required is a transformer providing 30 V at 1 A and a fuse. Actually 30 W is more power than is needed except in the interests of a short warm-up time, the latent heat ballasting being so effective in reducing temperature cycling, that it is unnecessary to keep the oven power low in order to avoid temperature overshoots. The switching cycle is approximately 20 seconds on and 80 seconds off at an ambient temperature of 20° C.

4. Performance

The effectiveness of a crystal oven is determined by its performance in shielding the crystal from changes in ambient temperature, by its ability to maintain a constant temperature without cycling, and by the speed with which it reaches its operating temperature when warming up. Twelve ovens have been subjected to tests to determine their performance in these respects.

Since direct measurements of small temperature differences are difficult to make, use was made of a crystal of similar construction and dimensions to the normal type but having a known, large, temperature coefficient of frequency at the oven temperature. This crystal, mounted within the oven under test, was used to control the frequency of an oscillator and recordings were made of this oscillator frequency over periods of time during which the oven was subjected to ambient temperature changes, the oscillator circuitry being maintained at a sensibly constant ambient temperature. A description of the method used in making these recordings is given in the Appendix.

The curve shown in Fig. 7 is a reproduction of a typical recording made of the test crystal oscillator frequency over a period during which the ambient temperature was reduced by 14·5 deg C. The horizontal units represent frequency in cycles per second above 5 Mc/s and this is plotted against time in hours. The shift of frequency is 2·1 c/s and the temperature coefficient of frequency of the crystal used was 25 c/s deg^{-1} C. Thus the temperature change within the oven was 0·084 deg C which, for a change of ambient temperature of 14·5 deg C, gives the oven an improvement factor of 173. While this result is not particularly good it will, no doubt, be improved upon as the technique advances. The temperature coefficient of the normal crystal at the extreme limit of the manufacturing tolerance (i.e. at $\pm$ 3 deg C away from the temperature of zero temperature coefficient) is 5 parts in 10^7 deg^{-1} C. Thus, with an improvement factor of 173, the shift of frequency produced by a 10 deg C shift of ambient temperature, would be 2·8 parts in 10^8.

The recording of Fig. 7 also reveals that the effect of oven cycling is completely negligible for most practical purposes. The extent of the cycling error is shown by the width of the line, estimated to amount to about $\pm$ 0·035 cycles/sec. This is equivalent to a temperature change within the oven of $\pm$ 0·0014 deg C. Using a normal crystal, again at the extreme limit of its temperature coefficient tolerance, this

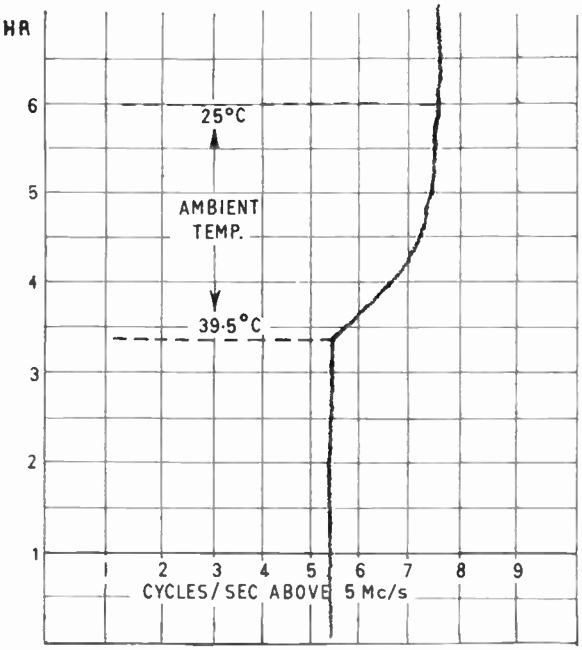

Fig. 7. Recording of the variation of test crystal oscillator frequency with a change in ambient temperature. Temperature coefficient of the crystal was 25 c/s deg^{-1} C.

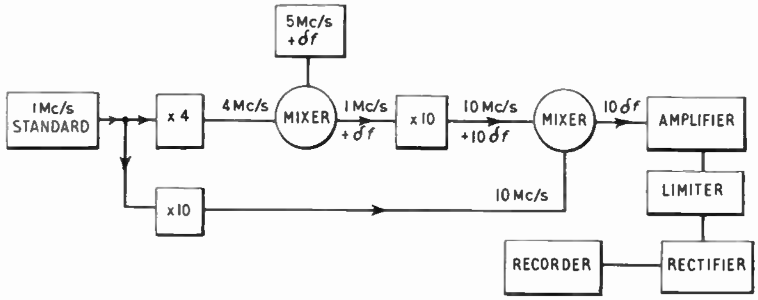

Fig. 8. Test arrangement for determining frequency errors.

temperature change would cause a frequency error of ± 7 parts in 10^{10}.

Measurements of the warm-up time of this oven show that the oscillator frequency approaches within 1 part in 10^6 of the final frequency in 15 minutes and within 1 part in 10^7 in 35 minutes.

In view of the early design difficulties which were encountered when ovens were allowed to cool, five ovens were subjected to daily heating and cooling cycles. When the highest precision is aimed at, such cycling should be avoided and the ovens left running since crystals tend to repeat their ageing cycles if subjected to thermal shock. Nevertheless the following results are worth noting. One hundred switching operations were carried out and whenever a final frequency measurement differed from the preceding one, the difference was noted as an error. For the 100 operations the average error was 0·168 c/s at 5 Mc/s or 3·4 parts in 10^8.

The oven by virtue of its operating principle cannot contribute anything to long-term ageing errors. Such drifts can be attributed to the crystal and to the oscillator circuit. The actual crystals used in these experiments were series resonant 5 Mc/s BT cut with glass envelopes and flying leads. No ageing effects greater than 2 parts in 10^7 over three months were obtained.

5. Acknowledgment

The author wishes to thank the Engineer-in-Chief of Marconi's Wireless Telegraph Co. Ltd. for permission to publish this paper. He also acknowledges with thanks the help and encouragement he has received from Mr. R. J. Kemp and Dr. G. L. Grisdale.

6. Appendix: Recording Frequency Errors

The method used in making the recording, such as is shown in Fig. 7, is best understood by referring to the block diagram of Fig. 8.

The output of the oscillator under test, in this case a frequency of 5 Mc/s, plus an error, was fed to a mixer together with the fourth harmonic of a standard 1 Mc/s frequency. The resulting beat frequency was thus 1 Mc/s + δf, δf being the frequency error of the 5 Mc/s oscillator relative to the standard. This beat frequency was fed to a multiplier circuit providing an output of 10 Mc/s + $10\delta f$ and this multiplied frequency was fed to another mixer together with the tenth harmonic of the standard frequency, the output of the mixer being $10\delta f$. The multiplied error signal was amplified, limited and fed to a rectifier arranged to produce a direct voltage proportional to the input frequency. A 100-microamperes movement recorder measured and recorded this voltage, the circuit parameters being chosen so that the recording meter calibration read directly in cycles/second error above or below 5 Mc/s.

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Symmetrical Transistors as A.C. or D.C. Switches and their Applications in Modulator and Demodulator Circuits

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Presented at the South Western Section's Convention on "Aviation Electronics and its Industrial Applications", held in Bristol on 7th–8th October 1960.

Summary: It is shown that a symmetrical circuit containing a symmetrical or near symmetrical transistor should exhibit lower voltage and current drift than the more conventional circuits. A circuit with asymmetry complementary to a near symmetrical transistor will perform almost as well as the symmetrical circuit and will have zero "contact potential". Test results demonstrate that an equivalent input circuit drift rate in the range ± 1·5 μV/deg C from – 40° C to + 100° C can be expected for a very large percentage of any batch. The relationship between drift rate, circuit impedance and ambient temperature is examined. Various applications of these switches are discussed including modulators, demodulators and precision a.c. switches.

List of Symbols

I_0	transistor switch leakage current
I_B	total base current
I_C	collector current
I_{CO}	collector leakage current
I_E	emitter current
I_S	signal current
r	incremental transistor "on" impedance
r_T	incremental transistor "on" impedance at temperature T
R	"off" resistance of transistor
V_0	$\frac{kT}{q}$ where k = Boltzmann's constant; T = temperature (absolute); q = electronic charge
V_{CE}	collector emitter voltage
V_{CEO}	collector emitter voltage at $I_S = 0$
$V_{CEO(T)}$	collector emitter voltage at $I_S = 0$ and at temperature T
α_F	grounded base current gain, normal operation
α_R	grounded base current gain, inverted operation
β_F	grounded emitter current gain, normal operation
β_R	grounded emitter current gain, inverted operation

1. Introduction

The work described in this paper was initiated in order to study the use of thermocouple transistor amplifiers in control systems required to operate over a wide temperature range and at high levels of vibration. This paper discusses the theoretical treatment of transistor switch circuits and investigates the results obtained with a new type of symmetrical silicon alloy transistor in a symmetrical and a near symmetrical circuit. A typical example of the need for such an amplifier is the control of jet-pipe temperature in a gas turbine where the thermocouple normally employed has an output of 40 μV/deg C. An accuracy of ± 5 deg C is required of the system, of which about ± 2 deg C is permissible in the amplifier. It was thought that the use of a transistor chopper amplifier would simplify initial adjustments, lead to a significant reduction in size and weight and achieve a wider frequency response than a magnetic amplifier. A preliminary review led to the conclusion that the chopper circuit described by G. H. Cole[1] using a transistor switch with symmetrical base drive was the most promising‡.

2. Transistor Switch Circuit

A number of possible transistor switch circuits are shown in Fig. 1. These circuits are drawn for *pnp* transistors: the extension to *npn* types is an obvious possibility. It may be seen that the symmetrical circuit of Fig. 1 (d) reduces effectively to that of Fig. 1 (a) if $R_1 = \infty$, and to that of Fig. 1 (b) if $R_2 = \infty$. Further, if R_2 of Fig. 1 (c) is very small, this circuit only differs from Fig. 1 (a) or (b) by the amount of a small-fixed voltage in series with the switch terminals. It follows that in order to study the transistor as a switch it is only necessary to consider the circuit of Fig. 1 (d).

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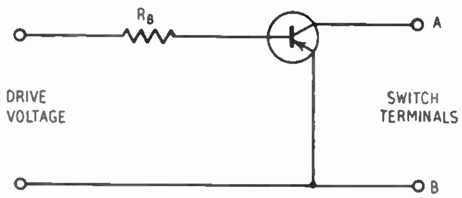
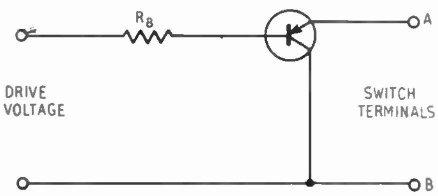
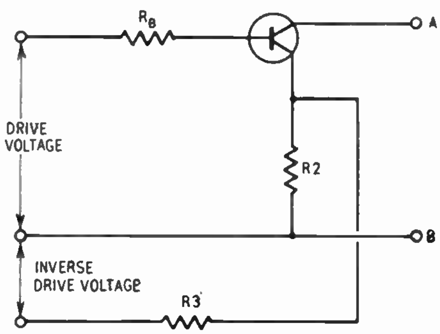
‡ Later work in the laboratory has shown that the Hall effect modulator can achieve equally low drift levels at the expense of reduced efficiency.



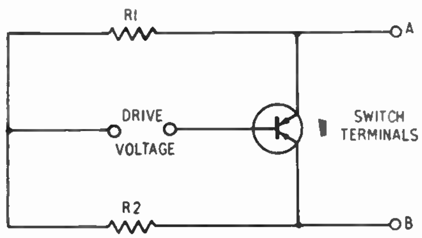
(a) Asymmetric circuit - normal operation



(b) Asymmetric circuit - inverted operation



(c) Asymmetric circuit of (a) or (b) with balancing. R2 is a few ohms only



(d) Symmetrical circuit

Fig. 1. Various possible switch circuits.

The equivalent circuits of such a switch are shown in Figs. 2 (a) and (b). For efficient operation r, the "on resistance", should be small and R, the "off resistance", large, compared with the impedance of the external circuit; also V_{CEO} and I_0 must be small. For stable operation in a feedback circuit V_{CEO} and I_0 should have low temperature coefficients; in open loop circuits it may be necessary to consider also the stability of r and R.

3. Forward Bias Condition

In the Appendix it is shown that the parameters r and V_{CEO} of the "on" equivalent circuit are related to the real circuit parameters by the following equations:

$$\text{for } I_S \ll \beta_F I_B \qquad r \simeq \frac{V_0}{\beta_F I_B}(1+x) \qquad \ldots\ldots(1)$$

which is independent of the ratio R_1/R_2 and is thus true for all circuits (see also eqn. (40)).

In the above equation the parameters are defined as

$$V_0 = \frac{kT}{q} \simeq 26 \text{ millivolts at } 25^\circ \text{ C}$$

$$I_B = \text{total base current}$$

$$x = \frac{\beta_F}{\beta_R} = \frac{\text{forward current gain}}{\text{reverse current gain}}$$

also

$$V_{CEO} = \frac{V_0}{2\beta_F}\{(1+\delta)-x(1-\delta)\} \qquad \ldots\ldots(2)$$

(see also eqn. (37))

or

$$V_{CEO} = \frac{V_0}{2}\left\{\frac{(1+\delta)}{\beta_F} - \frac{(1-\delta)}{\beta_R}\right\} \qquad \ldots\ldots(3)$$

(see also eqn. (38))

where

$$\frac{1+\delta}{1-\delta} = \frac{R_2}{R_1} \qquad \ldots\ldots(4)$$

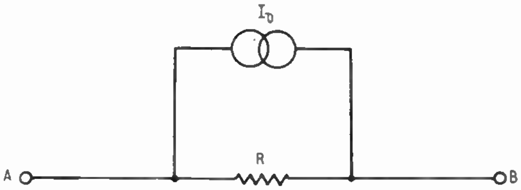
Thus for the asymmetric circuits of Fig. 1 (a) we have, putting $R_1 = \infty$, i.e. $\delta = -1$,

$$V_{CEO} = -\frac{V_0}{\beta_R} \qquad \ldots\ldots(5)$$

and for Fig. 1 (b), putting $R_2 = \infty$, i.e. $\delta = +1$,

$$V_{CEO} = \frac{V_0}{\beta_F} \qquad \ldots\ldots(6)$$

(a) Equivalent circuit in 'on' condition



(b) Equivalent circuit in 'off' condition

Fig. 2. Equivalent circuits of transistor switch.

The change in sign is due to an inversion of terminals A and B in the transformation between Fig. 1 (d) and (b).

For a truly symmetrical circuit $\delta = 0$, then

$$V_{CEO} = \frac{V_0}{2\beta_F}(1-x) = \frac{V_0}{4\beta_M}\frac{(1-x^2)}{x} \qquad \ldots\ldots(7)$$

where $\beta_M = \dfrac{\beta_F+\beta_R}{2}$ = mean current gain.

The temperature coefficient of V_{CEO} can be evaluated by differentiating eqns. (2), (5) or (6) with respect to temperature.

By differentiating eqn. (2), and assuming δ is a constant,

$$\frac{dV_{CEO}}{dT} = \frac{-V_0}{2\beta_F}\frac{dx}{dT}(1-\delta) + \frac{2\beta_F\dfrac{dV_0}{dT} - 2V_0\dfrac{d\beta_F}{dT}}{4\beta_F^2}\{(1+\delta)-x(1-\delta)\}$$

Employing $V_{CEO(T)}$ as the value of V_{CEO} at $T°$ C gives

$$\frac{dV_{CEO}}{dT} = -\frac{V_0}{2\beta_F}(1-\delta)\frac{dx}{dT} + V_{CEO(T)}\left\{\frac{1}{V_0}\frac{dV_0}{dT} - \frac{1}{\beta_F}\frac{d\beta_F}{dT}\right\} \ldots\ldots(8)$$

which is independent of δ provided that $V_{CEO(T)}$ is measured for the value of δ in use.

This means that in a symmetrical circuit in which δ is chosen to make V_{CEO} zero at room temperature

$$\frac{dV_{CEO(T)}}{dT} = \frac{V_0}{2\beta_F}\frac{dx}{dT} \qquad \ldots\ldots(9)$$

since from (2), δ is small for $x \simeq 1$.

For the asymmetrical circuits it is more convenient to differentiate eqns. (5) or (6) whence

$$\frac{dV_{CEO}}{dT} = V_{CEO(T)}\left\{\frac{1}{\beta_R}\frac{d\beta_R}{dT} - \frac{1}{V_0}\frac{dV_0}{dT}\right\} \ldots\ldots(10)$$

Palmer[2] has shown that for silicon alloy transistors similar to those used in this investigation $\dfrac{1}{\beta}\dfrac{d\beta}{dT}$ at 25° C lies between the limits of $3{\cdot}1 \times 10^{-3}$ and $4{\cdot}8 \times 10^{-3}$.

Now $$\frac{dV_0}{dT} = \frac{k}{q} = \frac{V_0}{T}$$

Hence $$\frac{1}{V_0}\frac{dV_0}{dT} = \frac{1}{T} \simeq 3{\cdot}3 \times 10^{-3}$$

This leads to a value of dV_{CEO}/dT between the limits of $V_{CEO} \times (+1{\cdot}5 \times 10^{-3})$ and $V_{CEO} \times (-0{\cdot}2 \times 10^{-3})$ for the asymmetrical circuit.

In the case of a symmetrical circuit with $V_{CEO(T)} = 0$ we have from eqn. (9)

$$\frac{dV_{CEO}}{dT} = \frac{-V_0}{2\beta_F}\frac{d}{dT}\left(\frac{\beta_F}{\beta_R}\right) = \frac{-V_0}{2\beta_F}\,\frac{\beta_R\dfrac{d\beta_F}{dT} - \beta_F\dfrac{d\beta_R}{dT}}{\beta_R^2}$$

Now $$\frac{V_0}{2\beta_F} = \frac{rI_B}{4(1+x)}$$

Also, putting $$\frac{1}{\beta_F}\frac{d\beta_F}{dT} = K_1$$

and $$\frac{1}{\beta_R}\frac{d\beta_R}{dT} = K_2$$

then $$\frac{dV_{CEO}}{dT} \simeq \frac{rI_B x}{4(1+x)}(K_2-K_1) \qquad \ldots\ldots(11)$$

Using Palmer's results for the limiting values of K_1 and K_2

$$\left|\frac{dV_{CEO}}{dT}\right| < rI_B\frac{x}{(1+x)} \times 0{\cdot}4 \times 10^{-3}$$

or, since x is near unity, $\beta > 10$ and $V_0 = 26$ mV, then

$$\left|\frac{dV_{CEO}}{dT}\right| < x \times 10^{-6} \text{ volts/deg C}$$

Where $V_{CEO} \neq 0$ the overall drift will be given by

$$\frac{dV_{CEO}}{dT} = K_3 V_{CEO} + K_4\frac{2V_0}{\beta} \qquad \ldots\ldots(12)$$

where K_3 lies between $1{\cdot}5 \times 10^{-3}$ and $-0{\cdot}2 \times 10^{-3}$ and K_4 lies between $\pm 0{\cdot}4 \times 10^{-3}$

(N.B. K_3 is obtained as for the asymmetrical circuit.)

In order to find dr/dT we must differentiate eqn. (1) whence

$$\frac{dr}{dT} = \frac{(1+x)}{I_B}\,\frac{\beta_F\dfrac{dV_0}{dT} - V_0\dfrac{d\beta_F}{dT}}{\beta_F^2} + \frac{V_0}{\beta_F I_B}\frac{dx}{dT}$$

$$= \frac{(1+x)}{\beta_F I_B}\frac{dV_0}{dT} - \frac{V_0(1+x)}{\beta_F^2 I_B}\frac{d\beta_F}{dT} + \frac{V_0}{\beta_F I_B}\frac{dx}{dT}$$

Therefore

$$\frac{dr}{dT} = r_T\left(\frac{1}{V_{0(T)}}\frac{dV_0}{dT} - \frac{1}{\beta_{F(T)}}\frac{d\beta_F}{dT} + \frac{1}{(1+x)}\frac{dx}{dT}\right)$$

From which it is seen that the percentage drift in r will be very similar to the percentage drift in V_{CEO}.

4. Reverse Bias Conditions

It is shown in the Appendix that the emitter and collector currents in the reverse bias condition are given by

$$I_C = \frac{I_{CO}(1-\alpha_R)}{(1-\alpha_F\alpha_R)}$$

$$I_E = \frac{I_{CO}\left(\frac{\alpha_R}{\alpha_F} - \alpha_R\right)}{(1-\alpha_F\alpha_R)}$$

For the asymmetric circuits it follows that

$$I_0 = \frac{I_{CO}(1-\alpha_R)}{(1-\alpha_F\alpha_R)} \qquad \ldots\ldots(13)$$

and for the symmetrical circuit $I_0 = I_C - I_E$

Therefore

$$I_0 = \frac{\left(1-\frac{\alpha_R}{\alpha_F}\right)}{(1-\alpha_F\alpha_R)} \qquad \ldots\ldots(14)$$

Thus the symmetrical circuit can have zero I_0 with finite values of β. However the "off resistance" R is higher in the asymmetric case, since it is the collector impedance of the transistor and may be many megohms. In the symmetrical case this impedance is shunted by (R_1+R_2).

5. Choice of Operating Bias

5.1. *Forward Bias*

The forward bias current controls the on resistance of the switch, and to a lesser extent the drift rate. It can be shown[3] that $1/\beta$ has the following form

$$\frac{1}{\beta} = G_{(2)}C_1 + \frac{1}{\beta_M}(1+C_2 I_E) \qquad \ldots\ldots(15)$$

where $G_{(2)}$ falls from 1 at very low emitter currents to $\frac{1}{2}$ at a few milliamperes.

Thus if V_{CEO} is plotted against I_B, curves are obtained as in Fig. 3 since $V_{CEO} \propto 1/\beta$. It will be seen that dV_{CEO}/dI_B is zero for base currents of about 200 μA and hence the choice of this value for I_B will stabilize the circuit against drive voltage variations. Early experiments also showed that dV_{CEO}/dT has a minimum at about this same value of base current.

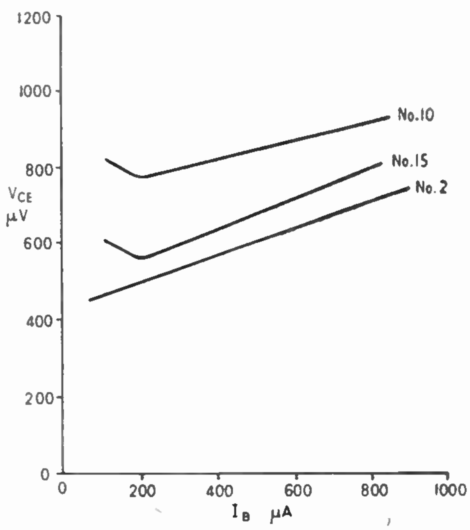


Fig. 3. Relationship between V_{CE} and I_B.

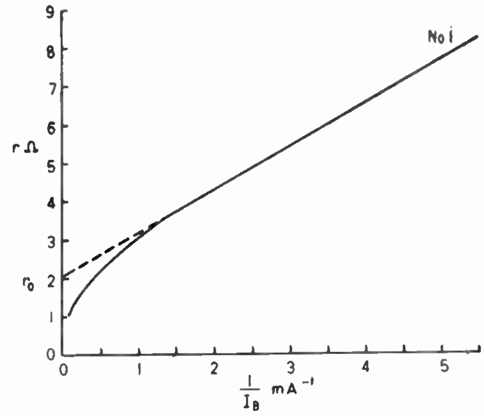


Fig. 4. Relationship between r and $\frac{1}{I_B}$

The variation of switch resistance r with I_B can be obtained from eqns. (1) and (15) giving

$$r = \frac{\text{const}}{I_B} + r_0 \text{ for constant } G_{(1)} \qquad \ldots\ldots(16)$$

At very low values of I_B, r will be higher due to variations of $G_{(2)}$, and at very high values of I_B, decrease of V_0 to about one half of its normal value[4] halves the minimum obtainable r. This is shown in Fig. 4.

5.2. *Reverse Bias*

Apart from the obvious conclusion that minimum leakage current will be obtained with minimum bias, it must be remembered that it is necessary to ensure that the collector and emitter have a reverse bias under all signal conditions.

In order to obtain a sufficient forward bias using a drive voltage which is symmetrical about zero, the reverse bias may be much higher than optimum. In this case it may be advantageous to limit the reverse bias by a diode network.

6. Experimental Results

Most of the experimental results have been obtained with the 400 c/s chopper circuit of Fig. 5. In practice up to twelve transistors could be switched in turn into the test position. These transistors were mounted in an oil bath, all the connections between the transistors and the cables being immersed in the oil which was well stirred.

All measurements were made by adjusting the voltage source until the reference reading on the phase sensitive valve voltmeter was zero. The results were recorded as an initial offset, i.e. the value of

V_{CEO} at ambient temperature, together with the variation from this V_{CEO} at temperatures in the range $-40°$ C to $+100°$ C. The potentiometer VR1 enables capacitances in the input circuit to be balanced, and with its use the "spikes" normally present in these circuits can be virtually eliminated. If the source impedance of the d.c. input is increased it becomes impossible to eliminate these spikes and care must be taken to avoid overloading the phase sensitive detector. For input impedances above a few hundred ohms a full-wave circuit is advantageous in order to avoid capacitance pickup in the "off" condition.

The first measurements were made with TS4, TS7, TS8 and XS101 germanium transistors. These gave encouraging results particularly the TS7, TS8 and XS101 transistors, but the maximum operating temperature was in the region of 45° C. It was therefore decided to carry out tests on some symmetrical silicon transistors.

At first the best available were the 2N495 selected for low V_{CE} at $I_C = I_E = \frac{1}{2}I_B = 100\ \mu A$. These transistors were cycled from $-40°$ C to $+100°$ C and typical drift rates are plotted against V_{CEO} in Fig. 6.

These results indicated that a more symmetrical transistor would give even lower drift rates and as a result a specification was prepared and discussed with various manufacturers. Semiconductors Ltd. were able to modify the 2N495 process in order to meet these requirements. An abridged version of the specification for this transistor is shown below:

$$I_{CO} < 0{\cdot}01\ \mu A\ ;\ I_{EO} < 0{\cdot}01\ \mu A$$

$$\beta_F > 10;\ \beta_R > 5;\ 2 > x > \tfrac{1}{2}$$

$|V_{CEO}|$ at $I_C = I_E = \frac{1}{2}I_B = 100\mu A$ shall not be greater than 1 mV.

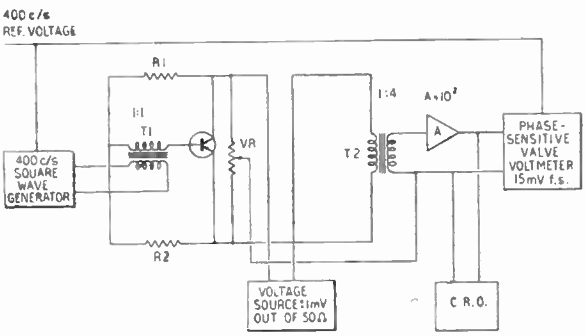


Fig. 5. The 400 c/s chopper circuit.

Typical drift curves for this transistor are shown in Fig. 6 and the values obtained for dV_{CEO}/dT are plotted against V_{CEO} in Fig. 7.

A statistical analysis of the variation of dV_{CEO}/dT with V_{CEO} and r/I_B measured by the slope of Fig. 4

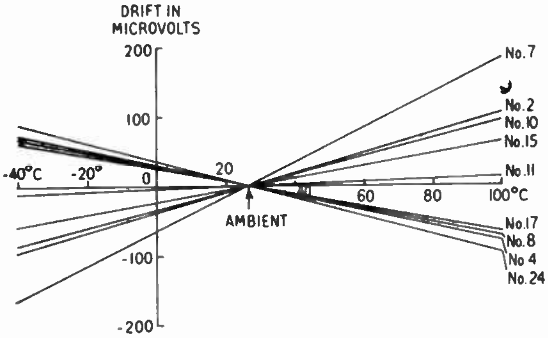


Fig. 6. Mean drifts for 9 EXP31 transistors.

gives the relationship

$$\frac{dV_{CEO}}{dT} = 1{\cdot}44 \times 10^{-3}\ V_{CEO} + 0{\cdot}361\ \frac{r}{I_B} - 0{\cdot}46 \quad \ldots\ldots(17)$$

where dV_{CEO}/dT is measured in μV/deg C and V_{CEO} and r/I_B are in millivolts. The variance was 0·23 μV/deg C.

This is in reasonable agreement with the predictions of eqn. (12) and as a result it was felt that a maximum drift of $\pm$ 1·5 μV/deg C would be obtained for a very high proportion of any batch of transistors used in a circuit giving $V_{CEO} = 0$ at any one temperature.

A second batch of experimental symmetrical silicon alloy transistors has now been obtained and preliminary results are very similar to those obtained with the first batch.

It is planned to carry out measurements of dV_{CEO}/dT for various values of δ so that the predictions of eqn. (12) may be further verified.

A small number of measurements have been made under d.c. conditions and the results agree with those obtained in a chopper circuit. In addition, current drift has been measured under d.c. conditions. It is found that I_0 may be as low as 0·31 μA at 80° C for a germanium transistor, thus confirming the low values for I_0 which can be predicted from eqn. (14) when $x \simeq 1$. For a series of silicon transistors at 80° C no transistor showed a value of I_0 greater than 0·01 μA.

Other experiments carried out to investigate the circuit as a high impedance modulator (Fig. 8) showed that care would be necessary in the associated transformer design. This would demand a very low distributed capacitance and capacitance to earth with, in particular, a high primary inductance for transformer T2, and low inter-winding capacitance for T1. Apart from these design considerations it may be claimed that the circuit of Fig. 8 can be used with very considerable advantage in a large number of applications where a diode modulator would normally be used. In particular, if the pairs of resistors R are

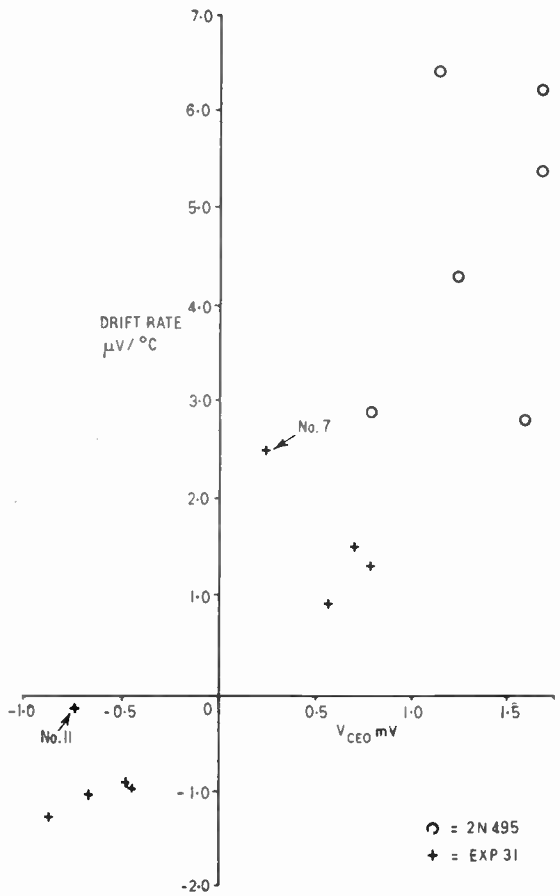


Fig. 7. Scatter diagram of mean drift rate versus V_{CE} at $I_C = I_E = \frac{1}{2}I_B = 100$ µA for transistors 2N495 and EXP31.

matched, the maximum unbalance will be < 1 mV with no further adjustments. Maximum d.c. inputs of 5 volts and maximum currents of tens of milliamperes are possible. The circuit of Fig. 8 can be used as a modulator or demodulator, and for smaller input signals the limiting circuit can be omitted.

7. Other Applications

The symmetrical transistor can be used as a precision a.c. switch, and the circuit of Fig. 9 shows a method of coupling two transformer windings with a single transistor. For this circuit ratios of "on" to "off" resistance have been achieved in the range 10^{-6}–10^{-7} to 1. If the two halves of the secondary of T1 are balanced for resistance no transients are caused by the switching action, thus in order to obtain very low transient levels it may be advantageous to put resistances in series with the emitter and collector. In order to achieve an accurate zero and a low output impedance in the off condition a second transistor may be used to short circuit the primary winding on transformer T2. This circuit, with the addition of a finite load, can be used as a variable gain control, provided that the signal voltage across the transistor is limited to a few tens of millivolts. Low impedances must be used in this application or the base currents required will be too close to I_{C0} for stable operation.

It has been demonstrated in the laboratory that this method of switching could be applied to a digital a.c. potentiometer with automatic nulling and with an a.c. accuracy of better than 0·1%.

8. Acknowledgments

The authors wish to thank Mr. K. Fearnside, Director of Research and Engineering of Smiths Aircraft Instruments Ltd., for permission to publish this paper, and Semiconductors Ltd. for their co-operation and assistance. The part played in this work by Messrs. C. M. Copage, A. G. Downing and J. B. Dunne is gratefully acknowledged.

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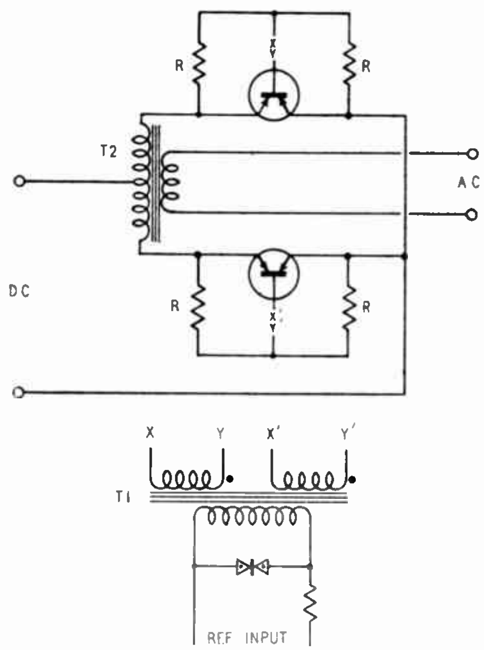

Fig. 8. High impedance modulator (or demodulator).

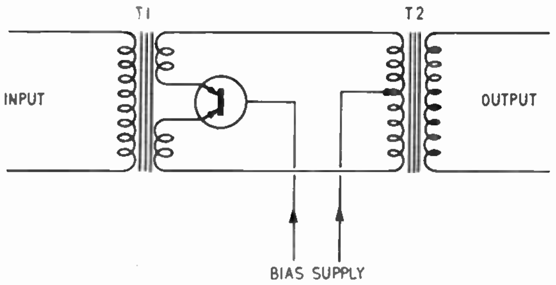

Fig. 9. Symmetrical transistor used as a.c. switch between two transformers.

10. Appendix

By the use of admittance parameters Ebers and Moll[5] deduce the following relationships for a transistor of generalized geometry:

$$I_E = a_{11}\phi_e + a_{12}\phi_c \qquad \ldots\ldots(18)$$

$$I_C = a_{21}\phi_e + a_{22}\phi_c \qquad \ldots\ldots(19)$$

where

$$\phi_e = \exp(V_E/V_0) - 1 \qquad \ldots\ldots(20)$$

$$\phi_c = \exp(V_C/V_0) - 1 \qquad \ldots\ldots(21)$$

and

$$V_0 = kT/q \qquad \ldots\ldots(22)$$

Reference 5 also gives

$$\frac{a_{21}}{a_{11}} = -\alpha_F \qquad \ldots\ldots(23)$$

$$\frac{a_{12}}{a_{22}} = -\alpha_R \qquad \ldots\ldots(24)$$

$$\frac{a_{12}a_{21}}{a_{11}} - a_{22} = I_{CO} \qquad \ldots\ldots(25)$$

$$\frac{a_{21}a_{12}}{a_{22}} - a_{11} = I_{EO} \qquad \ldots\ldots(26)$$

$$a_{12} = a_{21} \qquad \ldots\ldots(27)$$

Equations (18) and (19) can be solved for $V_C - V_E$ giving

$$V_C - V_E = -V_0 \log_e\left\{\frac{a_{12}I_C - a_{22}I_E + a_{21}a_{12} - a_{11}a_{22}}{a_{21}I_E - a_{11}I_C + a_{21}a_{12} - a_{11}a_{22}}\right\} \qquad \ldots\ldots(28)$$

Using eqns. (23) to (27)

$$V_C - V_E = -V_0 \log_e\left\{\frac{\alpha_F I_C + \dfrac{\alpha_F}{\alpha_R}(I_E - I_{CO})}{\alpha_F I_E + I_C - I_{CO}}\right\} \qquad \ldots\ldots(29)$$

Writing the term inside the bracket in the form $(1+\Delta)$ and using $\log(1+\Delta) = \Delta$ we obtain for $|(V_C - V_E)| \ngtr |V_0|$

$$V_C - V_E \simeq -V_0\left[\frac{I_C(\alpha_F - 1) + I_E\left(\dfrac{\alpha_F}{\alpha_R} - \alpha_F\right)}{\alpha_F I_E + I_C - I_{CO}}\right] \qquad \ldots\ldots(30)$$

Putting

$$I_C = \tfrac{1}{2}I_B(1+\delta) + I_S \qquad \ldots\ldots(31)$$

and

$$I_E = \tfrac{1}{2}I_B(1-\delta) + I_S \qquad \ldots\ldots(32)$$

where I_C is the signal current, whence from Fig. 1 (d),

$$\frac{R_1}{R_2} = \frac{1-\delta}{1+\delta} \qquad \ldots\ldots(33)$$

Equation (30) can now be re-written as

$$V_C - V_E \simeq -V_0\left[\frac{\tfrac{1}{2}I_B\left(\dfrac{\alpha_F}{\alpha_R} - 1\right) + (\tfrac{1}{2}I_B\delta + I_S)\left(2\alpha_F - 1 - \dfrac{\alpha_F}{\alpha_R}\right)}{\tfrac{1}{2}I_B(\alpha_F + 1) + \tfrac{1}{2}I_B\delta + I_S(\alpha_F - 1) - I_{CO}}\right] \qquad \ldots\ldots(34)$$

Dividing through by $(\alpha_F - 1)$ and putting

$$\alpha_F = \frac{\beta_F}{1+\beta_F}, \qquad \alpha_R = \frac{\beta_R}{1+\beta_R}, \qquad x = \frac{\beta_F}{\beta_R}$$

gives the approximation

$$V_C - V_E \simeq \frac{-V_0\{\tfrac{1}{2}I_B(1-x) + \tfrac{1}{2}I_B\delta(1+x) + I_S(1+x)\}}{-(2\beta_F + 1)\tfrac{1}{2}I_B + \tfrac{1}{2}I_B\delta + I_{CO}(\beta_F + 1) + I_S} \qquad \ldots\ldots(35)$$

Now the contact potential V_{CEO} can be obtained by putting $I_S = 0$.

Therefore

$$V_{CEO} \simeq \frac{V_0\{(1+\delta) - x(1-\delta)\}}{(2\beta_F + 1) - \delta - \dfrac{2I_{CO}}{I_B}(\beta_F + 1)} \qquad \ldots\ldots(36)$$

If $\beta_F \gg 1$, $2\beta_F I_{CO}/I_B \ll 1$ and $|\delta| < 1$

$$V_{CEO} \simeq \frac{V_0}{2\beta_F}\{(1+\delta) - x(1-\delta)\} \qquad \ldots\ldots(37)$$

or

$$V_{CEO} \simeq \frac{V_0}{2}\left\{\frac{(1+\delta)}{\beta_F} - \frac{(1-\delta)}{\beta_R}\right\} \qquad \ldots\ldots(38)$$

The incremental switch resistance r is given by

$$r = \frac{d(V_C - V_E)}{dI_S} = \frac{2V_0}{\beta_F}\left[\frac{(1+x)}{\left(1 + \dfrac{I_S}{\beta_F I_B}\right)^2}\right] \qquad \ldots\ldots(39)$$

For $\beta \gg 1$, $I_{CO} \ll \beta I_B$

and for small values of I_S this becomes

$$r = V_0(1+x)/\beta_F I_B \qquad \ldots\ldots(40)$$

The values of I_C and I_E under reverse bias conditions may be found by putting $\dfrac{V_E}{V_0} \gg 1$, and $\dfrac{V_C}{V_0} \gg 1$ in eqns. (20) and (21) and substituting in eqns. (18) and (19) whence

$$I_E = -a_{11} - a_{12}$$

$$I_C = -a_{21} - a_{22}$$

Using eqns. (23) to (27) we then get

$$I_E = \frac{I_{CO}\left(\dfrac{\alpha_R}{\alpha_F} - \alpha_R\right)}{(1 - \alpha_F\alpha_R)} \qquad \ldots\ldots(41)$$

$$I_C = \frac{I_{CO}(1 - \alpha_R)}{(1 - \alpha_F\alpha_R)} \qquad \ldots\ldots(42)$$

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New Satellite Tracking Station in Great Britain

A Minitrack Station, which will be operated by staff of the D.S.I.R.'s Radio Research Station, has been built at Winkfield, in Berkshire, for tracking satellites transmitting in the frequency band 136–137 Mc/s. The equipment has been supplied on loan by the National Aeronautics and Space Administration (N.A.S.A.) and the Station will be part of the world-wide network of the Minitrack System. (The term "Minitrack System" denotes a "minimum weight tracking system"—the weight naturally relating to the requirements of the satellite transmitter.)

The Station will be particularly valuable to British space research scientists when British instruments are flown in satellites to be launched by *Scout* rockets later this year. Another example of the use of the Minitrack Station will be the reception of the telemetered data from apparatus flown in satellites to investigate the upper portion of the ionosphere. The Radio Research Station is to collaborate with American and Canadian scientists in two "topside sounder" experiments of this kind by receiving the data at Winkfield and at its outstations at Singapore and in the Falkland Islands. The information obtained in this way about the upper side of the ionosphere will be complementary to that about the lower side which the Radio Research Station obtains from ground experiments.

Until recently there were ten Minitrack Stations, mainly in North and South America but including one in South Africa and another at Woomera in Australia. Originally set up to track satellites having orbits at comparatively small inclinations to the equator, this network is sited in low latitudes. The Winkfield installation is one of four additional stations to provide cover on satellites having orbits with higher inclination angles; the other three are in Minnesota, Alaska and Newfoundland. To enable Winkfield's observations to be accurately related to those of the other stations, the Ordnance Survey carried out detailed survey work which included the provision of markers precisely defined to within a 1 metre cube over which the aerials have been erected with an accuracy of $\pm\frac{1}{8}$ in. and ± 5 min of arc.

The Station is now ready for operation and has already been used for telemetry observations on 108 Mc/s—when *Explorer 8* was launched last November. It will come into full use as soon as satellites transmitting on 136–137 Mc/s are launched this year.

The tracking facility at Winkfield is of high precision and uses the interferometer principle to determine the direction of the satellite. The phase difference between radio signals received on aerials spaced apart at accurately known positions is measured: the phase difference represents the difference in time taken by the waves to reach the two aerials. By making simultaneous measurements on aerials set up on a North-South line and others on an East-West line the phase differences can be converted to give the angle in space of the satellite. Highest accuracy of angular measurement is given for a satellite immediately above the system; in this situation a precision of a few seconds of arc might be expected ideally, but in practice this is likely to be degraded to the order of a minute of arc corresponding to a movement of only a few hundred yards for a satellite at a height of, say, 400 miles.

The Interferometer Aerials.—There are two separate interferometers. One (called the equatorial system) responds to signals arriving from a few degrees on either side of a vertical plane lying in the north–south direction and the other (the polar system) to signals arriving from a corresponding zone on either side of an east–west vertical plane. Switching arrangements are incorporated so that either aerial system can be selected for connection to the receiver. For each interferometer the component aerials are accurately placed at the corners of a square whose diagonals are some 50 wavelengths long and are directed along the N–S and E–W directions. These aerials are called the "fine" aerials since the phase difference between them varies rapidly with satellite direction and provides a correspondingly high acuity in directional observations. They are identical in construction, each comprising eight horizontal co-linear elements connected in phase with a tapered amplitude distribution. The arrays are mounted above horizontal ground screens each 50 ft × 25 ft in size and all arrays are in the same horizontal plane (Fig. 1). The aerial arrays constituting the fine aerials of the equatorial system are arranged with the line of the component elements in the E–W direction and those for the polar system lie in the N–S direction. Thus each array has a vertically directed fan beam with a width between 3 dB points of 11 deg in the H plane and 76 deg in the E plane. The pick-up directivity pattern of each interferometer as a whole also has these characteristics since the fine aerials are all identical.

It is necessary to have auxiliary aerials called "ambiguity aerials", for measuring the integral number of 360 deg involved in the phase difference between the fine aerials since the phase measuring equipment connected to these provides only the accurate value of the fractional part of 360 deg. Thus, for example, consider a satellite crossing the N–S fan beam provided by the equatorial system. If its angle of elevation is 45 deg then the phase difference between the corresponding N and S fine aerials includes about 35×360 degrees since the path difference between the rays reaching these aerials is about

35 wavelengths. This difficulty is overcome by means of the five ambiguity aerials which are arranged at much closer spacings. The ambiguity aerials each consist of a single horizontal element mounted above an 18 foot square ground screen and have a vertically directed directivity pattern about 95 deg wide in both E and H planes.

The Phase Measuring Receivers.—All aerials are connected to the receivers by buried low-loss aluminium sheathed coaxial cable which is pressurized with dry nitrogen with the object of achieving stable transmission characteristics. The cables terminate in a console where remotely operated coaxial switches are located and serve to select either the polar or equatorial system for connection to the receiver. Let us assume that the polar system has been selected. Then the cables from the following aerials are connected through to the receiver North polar fine, South polar fine, East polar fine, West polar fine, and all five ambiguity aerials. To enable the direction of the satellite to be determined the following six phase differences have to be measured: N–S fine, E–W fine, N–S medium, N–S coarse, E–W medium and E–W coarse.

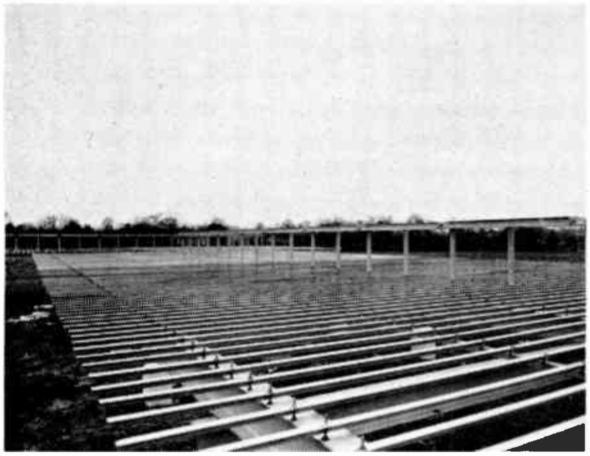

Fig. 1. Close-up of one of the "fine" aerials of the Minitrack interferometer systems. This consists of eight slot aerials mounted above a precisely located earth plane. There are four such pairs of aerials as well as "ambiguity aerials" of rather similar construction which together comprise the two interferometer systems.

The receiver has thus to be provided with six channels. These are identical in characteristics so we need only outline the process involved in the N–S fine determination. The signals from the N and S fine aerials pass through separate preamplifiers and are then converted by frequency changers to intermediate frequencies differing from each other by precisely 100 c/s. The beating oscillators are crystal-controlled and the 100 c/s frequency difference required for the frequency conversion is phase-locked to a standard 100 c/s voltage obtained from a precision 1 Mc/s oscillator. Thus the original phase-difference between the N and S fine signal-frequency input voltages is represented by the phase of the 100 c/s beat note at the output of the receiver channel relative to that of the 100 c/s reference frequency.

This phase difference is presented in two ways, as a d.c. analogue voltage and in digital form. In the latter case the two 100 c/s voltages operate a gate system which counts the number of cycles of 100 kc/s which fit in the time interval between corresponding points in the two 100 c/s waveforms. Thus each 360 deg of 100 c/s phase difference (and therefore of the signal frequency phase difference) is split into 1000 parts and the digital display therefore has a phase discrimination of 0·36 deg.

The analogue and digital voltages (the latter in the form of a decimal code, read out five times a second) are applied to separate pen-type recorders, a separate stylus being used for each of the six receiver channels (that is, aerial combinations). Additional channels on the recorders are used for indicating time and to record the signal strength.

Facilities are provided to reference the phase-measuring system by injecting locally generated co-phasal voltages into the signal frequency pre-amplifiers. The receiver is crystal controlled and the operating frequency is selected remotely at the control console, 1000 steps at 1 kc/s intervals being provided in the frequency band 136–137 Mc/s. The pre-detection bandwidth of each of the six main channels of the receiver is 10 kc/s. An input of about −120 dBm is required to give a reliable read-out on the digital phase meter, corresponding to an overhead range of about 1500 miles on a 10 mW transmitter.

Calibration of the Interferometer.—To check on the overall behaviour of the polar and equatorial interferometers as direction finders it is necessary to calibrate them from time to time. This is done by means of a high flying aircraft carrying a lamp which is switched on at known times, and photographing the track of the light against the star background which is used as a reference. At the instant the lamp is flashed on, the digital phase meter channels are recorded for the signal arriving from an extremely low power c.w. transmitter carried in the aircraft. Considerable directional acuity is provided by the interferometers; a change of 360 deg in phase difference between the fine aerials is produced by an angular movement from the zenith of about 1·2 deg and angular changes of one thousandth of this are potentially detectable on the digital phase meter. Thus high precision photography and timing accuracy are required. The camera used is permanently mounted at the centre of the system; it has a focal length of 40 in. and is mounted on a polar axis and driven so that star images remain stationary on the plate. The lamp on the aircraft is mounted at the centre of a downward-pointing circularly polarized aerial which is fed by the transmitter operating on a frequency in the band 136–137 Mc/s. The aircraft also carries a receiver which picks up coded timing signals from a ground transmitter for flashing on the aircraft lamp; these signals are the same as those which are used for time-marking the interferometer records. Thus the photographic plate provides via the trace of the flashing lamp and the star background the angular position of the aircraft relative to the centre of the interferometer system while the interferometer records provide the corresponding angular information for the radio system at the same points of time. The first calibration of the system was carried out in December but the results are not yet available.

Telemetry Receiving System.—The final 136–137 Mc/s receiving system for telemetry has not yet been installed but experience has been gained, using signals on 108 Mc/s from *Explorer 8* launched on 3rd November. The final receiver will be much more flexible than the communication receiver used for 108 Mc/s but otherwise a description of the equipment used on this frequency is representative of that which will be used in the 136–137 Mc/s band.

The aerial consists of an arrangement of nine Yagi aerials in a 3 by 3 array; eight are used for reception, and the centre one is connected to a transmitter which is available when required for altering the operation of the satellite (for example, to cause it to transmit any recorded experimental data). Each Yagi is an assembly of crossed dipoles; thus from the receiving array two voltages are available, one corresponding to vertically polarized reception and the other to horizontal polarization. These two voltages are applied to low-noise preamplifiers at the base of the aerial system and the outputs are connected by buried feeders to the main building. Here arrangements are provided which permit the use of either of the two linear polarizations or the combination of the two voltages in phase quadrature so as to provide the equivalent of a circularly polarized receiving array. The single output from the combining unit is connected to the receiver input terminals. The whole aerial array can be oriented in any desired direction by remote control from the main building.

An eight channel magnetic tape recorder, with a frequency response extending to 250 kc/s, is used for recording the telemetry data together with ancillary information. The inputs to the channels of the recorder depend on the particular satellite. In the case of *Explorer 8* the detected output from the receiver was recorded on one channel; other signals were recorded as follows: the intermediate-frequency signal prior to detection shifted down to a lower carrier frequency of a few tens of kc/s; continuous signals of precisely known frequency used subsequently for servocontrol of tape speed on replay of the tape; coded signals providing accurate time reference; signal strength by way of the a.g.c. voltage from the receiver which is converted to a varying frequency for recording purposes; voice announcements.

Teleprinter Circuit.—A continuous teleprinter circuit is provided between Winkfield and Goddard Space Flight Centre and another leg of this is connected in parallel to the Radio Research Station at Slough. This is used for transmitting a wide range of information in both directions. Its main function so far as the operation of the Winkfield station is concerned is to provide predictions for forthcoming passes of satellites within the range of the station.

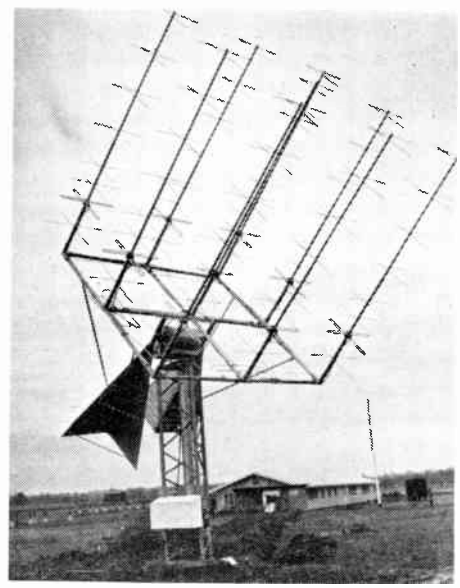

Fig. 2. A steerable telemetry aerial, used for receiving the results of experiments in satellites. This aerial operates on 108 Mc/s and is oriented from the main building; automatic following equipment may eventually be installed. Another similar aerial for 136–137 Mc/s telemetry signals—the new international frequency agreed for all future satellites—is nearly completed.

In the reverse direction its purpose is to pass back interferometer measurements and summarized telemetry data. There are also facilities for directly linking Winkfield (and R.R.S., Slough) to such research centres as the Smithsonian Astrophysical Observatory where optical observations on satellites are analysed.

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Contact Resistance Effects in Mechanical Choppers

By

I. C. HUTCHEON, M.A.†

Presented at the Symposium on New Components held in London on 26th–27th October 1960.

Summary: The contact resistance of a mechanical chopper is affected by several factors including, in particular, the type of contact material, the amount of sliding action between the contacts, and the local atmospheric environment. The paper discusses the results of tests involving more than 200 choppers of a particular design, in which these factors were varied. A high degree of reliability was obtained when contacts of suitable materials were operated with a slight degree of sliding and the choppers were free to breathe. Hermetic sealing was found to promote the growth of contact resistance.

1. Introduction

Despite advances in the design of other sorts of modulator, the mechanical chopper remains a competitive device and is still in widespread use. The low electrical drift, typically below 1 microvolt and 10^{-11} amp, makes it suitable for modulating low-level d.c. signals, while the high ratio of open to closed resistance, e.g. $10^8 : 1$ ohm, is valuable in other switching applications. The size and cost are not unreasonable, the power supply requirements are simple, and usually it is only the mechanical nature of the device which is regarded as a disadvantage.

This paper is concerned with the problems which arise in designing contacts for mechanical choppers. The main purpose is to maintain a low resistance between the contacts when they are closed, and at the same time to ensure a low rate of wear so that the chopper has a long life.

In most applications, the circuit voltages are so small that they do not break down any non-conducting films, no matter how thin, which form on the contact surfaces. It is therefore necessary to choose contact materials which are relatively immune to film formation, and at the same time to introduce a certain degree of sliding between the contacts to break down mechanically such films as do form.

If the degree of sliding is considerable, the choice of materials is less critical, but the life of the contacts may be short because of the high rate of mechanical wear. This approach is sometimes adopted in the design of choppers for expendable equipment.

For industrial use, where the life must extend over many years, only a limited amount of sliding can be tolerated, and the materials must be chosen more carefully. Only the noble metals and some of their alloys are suitable. At the same time it is necessary to avoid any particularly serious causes of film formation. Tests which are described in the paper have shown that choppers of a particular design, which are normally very reliable, develop substantial contact resistance when sealed in airtight containers. This is almost certainly due to a growing concentration of volatiles given off by some of the constructional materials having an organic base. To design a chopper using only inorganic materials is difficult, but satisfactory results are obtained by the simpler expedient of allowing the chopper to breathe through porous seals.

The results of tests on contact resistance generally show a very wide scatter, and it is necessary to test large numbers of contacts. The number of variables which can be changed is therefore small, and for this reason all the tests described in this paper were confined to one mechanical design. This, however, contained two types of contact, one operating with a small but well-defined sliding action, and the other operating with no sliding at all. The latter type of contact proved inadequately reliable. More than 200 choppers were tested altogether, involving 800 contact pairs. Preliminary tests were made to find suitable contact materials, and these were then standardized while changes were made in the methods of sealing.

2. Design of Chopper

Figure 1 shows the design of chopper which was used for all the tests. It is of the resonant-reed variety and operates at mains frequency.

It contains two pairs of contacts which have a slight sliding action and two pairs, whose use was discontinued as a result of the tests, which have no sliding action at all. Each contact pair is in the form of two

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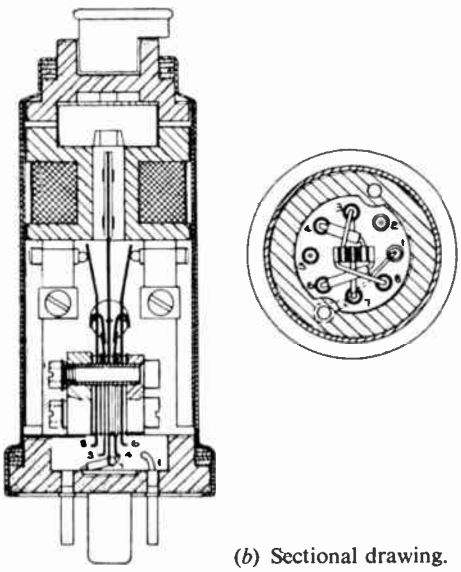
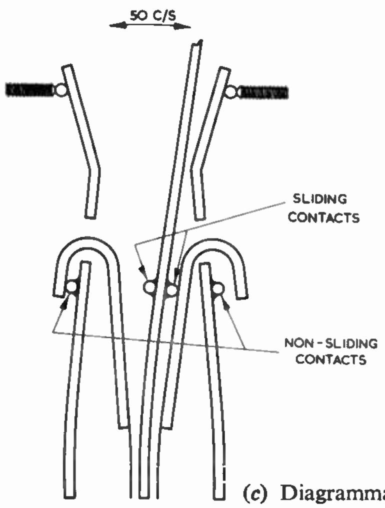
(*a*) Chopper with can removed.



(*b*) Sectional drawing.



(*c*) Diagrammatic layout.

Fig. 1. Mechanical chopper.

crossed cylinders of noble metal wire, 0·020 in. in diameter, and the contact pressure is about 8 gm in all cases.

The central reed is made to vibrate by a coil and permanent magnet. Two horizontal cylindrical contacts, mounted near its clamped end, mate with two hook-shaped wires and form the two pairs of sliding contacts. The outer ends of the hooks mate with horizontal contacts on two stiff but flexible reeds which can be adjusted to provide the desired waveform. In the vicinity of the contacts, the amplitude of vibration of the central reed is about ± 0·0017 in., and the sliding effects, calculated from the geometry of the system with the central reed treated as a simple flexible beam, are as given below.

Table 1

Sliding Effects at Contacts

	Central Contacts	Hooks	Total
Movement of point of contact along surface	±0·00006″	±0·00031″	±0·00037″

Visual checks using a microscope and stroboflash confirm that these figures are approximately correct. (It is interesting to note that the total sliding action, with 50 c/s operation, is about 7 miles per year in either direction.)

The area of metal-to-metal contact at the non-sliding pairs of contacts, calculated (Appendix 1) from the load and hardness of the material, is about 10^{-6} cm^2 for hard-drawn pure gold. This causes a constriction resistance, due to the concentration of current flow through the small area, of about 2×10^{-3} ohms. This is negligible, and the higher contact resistances often measured in practice must therefore be due to the presence of surface films.

3. Test Procedure

It was soon found that quite small mechanical shocks would often temporarily clear a fault, presumably by shifting slightly the point of contact along the contact surfaces. Consequently, all the tests were carried out with the choppers plugged into test racks mounted away from vibration, usually on a brick wall. Long flexible fly leads, attached to the racks and terminating in octal plugs, were used to connect each chopper in turn to the test circuit shown in Fig. 2.

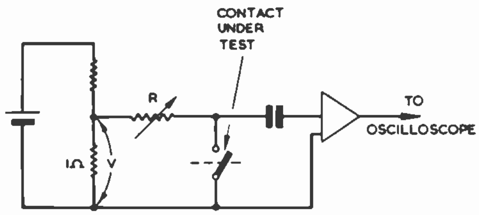


Fig. 2. Test circuit.

This circuit enables the waveform to be examined and the contact resistance to be estimated. A direct voltage V, normally about 10 mV so as not to break down any surface films, is applied to the contact under test via a variable resistance R. The resultant a.c. signal is displayed on an oscilloscope. Since the contact resistance is sometimes fairly constant throughout a half cycle, and sometimes varies widely, two observations of the value of R were made in each case. These were:

(a) The approximate value of R required to halve the trace amplitude. This value, denoted R_m, is equal to the mean contact resistance.

(b) The value of R, to the nearest order of magnitude, required to give a trace which appeared visually perfect. This value, R_p, is roughly one hundred times greater than the peak contact resistance.

Comparison of R_m and R_p enables some estimate to be made from recorded results of the type of waveform given by the contacts.

4. Effects of Different Contact Materials

Several scores of choppers were constructed with a variety of combinations of contact materials, and tested over periods up to more than a year. All were ventilated. At least three and more often six choppers were made of each type. The results of the tests are summarized below.

4.1. *Types of Waveform*

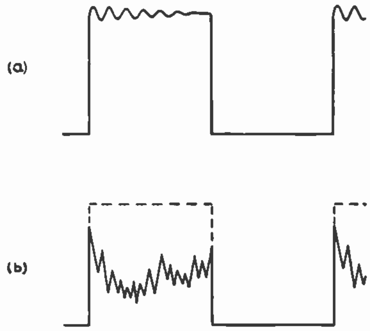
Non-sliding contacts usually gave a basically smooth steady square waveform (Fig. 3 (a)) indicating (as would be expected) unvarying contact resistance over the period of contact. The actual resistance was sometimes quite high, however, e.g. 10, 100 or more ohms, indicating the presence of unbroken surface films.

In many cases the trace was modified by a small damped train of superimposed oscillations at about 5 kc/s, starting at "make" due, it is presumed, to modulation of the film resistance by pressure fluctuations caused by a local mechanical resonance. In a few cases, with some contact materials, the waveform would grow and collapse erratically.

Sliding contacts gave a quite different trace, this generally being steady but peaky as shown in Fig. 3 (b). The same trace would be reproduced for days without variation, suggesting the presence of patches of high and low contact resistance on the contact faces. The actual mean resistance was usually below 10 ohms. Erratic growing and collapsing was never seen, and there was no superimposed ripple.

4.2. *Effect of Applied Voltage*

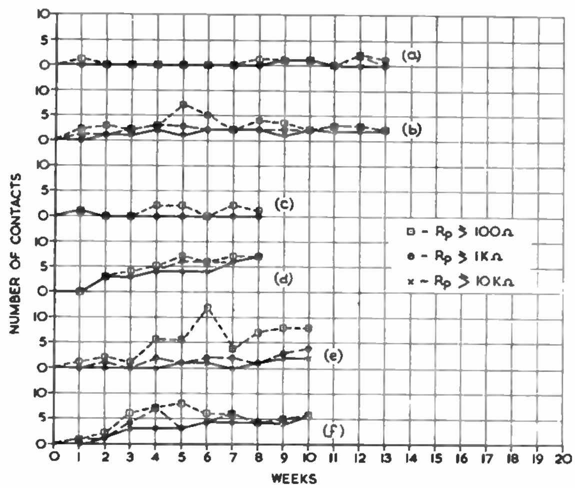
Waveforms were seldom altered appreciably by varying the applied voltage between 1 mV and 100 mV, and all tests were carried out at about 10 mV. Application of 1 volt would sometimes improve the waveform temporarily, and the application of 10 volts nearly always produced a perfect waveform which would remain for hours or days in the case of non-sliding contacts, but would deteriorate in a short time when there was a sliding action. These results can be explained as the result of coherer action whereby the films are broken down and penetrated by thin bridges of initially molten metal which immediately solidify. In the absence of sliding, the bridges would repeatedly mate up again, whereas any sliding action would rapidly wear them away.



(*a*) Non-sliding contacts. (*b*) Sliding contacts.

Fig. 3. Typical waveforms.

In two non-sliding cases, a high resistance contact existed at 10 mV to 1 V. When 10 V was applied a good waveform appeared briefly and then disappeared entirely. This may possibly be explained as being due to the explosion of metal bridges originally formed by penetration of thin parts of the film, combined with the presence around them of a thicker film which prevented further contact. Normally such bridges would increase in size and conductance until the voltage across them dropped to the melting voltage for the contact material in use. If they could not increase in size they would have to explode.



(*a*) Batch D: 20 choppers, 40 sliding contact pairs.
(*b*) Batch D: 20 choppers, 40 non-sliding contact pairs.
(*c*) Batch E: 21 choppers, 42 sliding contact pairs.
(*d*) Batch E: 21 choppers, 42 non-sliding contact pairs.
(*e*) Batch F: 30 choppers, 60 sliding contact pairs.
(*f*) Batch F: 30 choppers, 60 non-sliding contact pairs.

Fig. 6. Contact resistance of unsealed choppers.

of the few cases where slight contact resistance developed, it was rapidly cleared by the rubbing action.

Non-sliding contacts were also improved by the elimination of air-tight sealing. However, there was still a failure rate ($R_p \geqslant 10$ kΩ) of the order of 2 to 15% according to batch. A feature of these contacts is that occasional failures occur after many weeks of satisfactory operation, and are not self-correcting. The results obtained with non-sliding contacts are clearly not acceptable.

6. Conclusions

Tests carried out on a large number of mechanical choppers showed that:

(1) For complete reliability, the contacts must operate with at least a slight sliding action in order to break down thin non-conducting films on the contact surfaces. The sliding action must, however, be small enough to cause negligible wear.

(2) Of several combinations of contact materials giving low contact resistance, pure gold versus PGS alloy, and pure gold versus iridium-platinum alloys, were found to be particularly satisfactory.

(3) In designs using materials having an organic base (bakelite, etc.), the choppers must be sealed in a manner which allows them to breathe, since hermetic sealing does not allow the escape of volatile compounds liable to give rise to non-conducting films on the contact surfaces.

7. Acknowledgments

The directors of George Kent Ltd. are thanked for giving their permission for this paper to be published.

8. Appendix 1: Constriction Resistance

Even with careful grinding and polishing it is difficult to produce surfaces which are flat to better than 10^{-5} cm. Thus when two practical surfaces are brought together, they first touch at a few high points or asperities only.

Even light loads cause these asperities to deform first elastically, and then plastically until their total area is such that it can support the load. The total area of contact is then[1, 2]

$$A = \frac{W}{P_m} = \frac{W}{H} \simeq \frac{W}{3Y} \qquad \ldots\ldots(1)$$

where W = the load,

P_m = the mean pressure at the points of contact,

H = the hardness measured with a spherical indenter, and

Y = the elastic limit in tension.

If the two materials have different properties, it is those of the softer material which matter. If the material is capable of work hardening, Y may be taken as the elastic limit for the work-hardened material.

The area of apparent contact, due to elastic deformation of the bulk material, may be similar to that given above or much greater and, for the case of two crossed cylindrical surfaces of radius r, the radius of the area of apparent contact is

$$a = 1{\cdot}1 \left\{\frac{Wr}{2}\left(\frac{1}{E_1} + \frac{1}{E_2}\right)\right\}^{\frac{1}{3}} \qquad \ldots\ldots(2)$$

where E_1 and E_2 are Young's Moduli for the two materials and W is the load.

Any current flowing from one contact to the other is restricted to the small areas of contact, and this gives rise to a "constriction resistance"[1] between the contacts. For two perfectly clean metal surfaces which touch over a single circular area of radius a, the value is[1]

$$R = \frac{\rho_1 + \rho_2}{4a} \qquad \ldots\ldots(3)$$

where ρ_1 and ρ_2 are the resistivities of the materials.

If the surfaces touch at a number of widely spaced circular areas, the conductivities of these constrictions can be added provided that each individual area is known. If they touch at a number of closely spaced areas, the spacing must be known as well. It is useful to assume, however, that contact in fact takes place over a single circular area, since this gives an approximate estimate of constriction resistance which may be somewhat high, i.e. pessimistic.

mounted away from vibration, usually on a brick wall. Long flexible fly leads, attached to the racks and terminating in octal plugs, were used to connect each chopper in turn to the test circuit shown in Fig. 2.

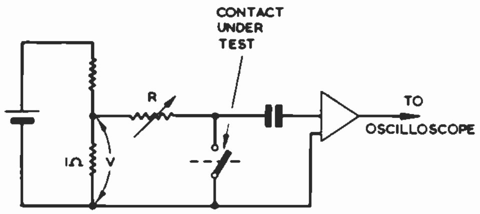


Fig. 2. Test circuit.

This circuit enables the waveform to be examined and the contact resistance to be estimated. A direct voltage V, normally about 10 mV so as not to break down any surface films, is applied to the contact under test via a variable resistance R. The resultant a.c. signal is displayed on an oscilloscope. Since the contact resistance is sometimes fairly constant throughout a half cycle, and sometimes varies widely, two observations of the value of R were made in each case. These were:

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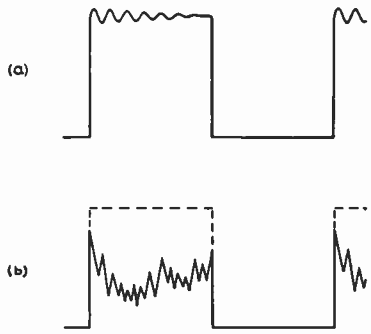

(*a*) Non-sliding contacts. (*b*) Sliding contacts.

Fig. 3. Typical waveforms.

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4.3. *Contact Materials Tested*

Table 2 gives the various combinations of contact materials which were tested. Except where stated, all were checked both with and without a sliding action. All, including pure gold, were in the form of hard-drawn wire.

Table 2

Contact Materials Tested

625 Alloy†	versus	625 alloy
P G S‡	,,	P G S
30% Ag-Au	,,	30% Ag-Au
Au	,,	Au
Au	,,	625 alloy
Au	,,	P G S
Au	,,	15% Ir-Pt (sliding only)
10% Ir-Pt	,,	10% Ir-Pt
10% Ir-Pt	,,	Pt
20% Ir-Pt	,,	Pt
20% Ir-Pt	,,	15% Ir-Pt

† Composition: 62·5% Au, remainder Ag and Cu.
‡ Composition: 7% Pt, 26% Ag, 67% Au.

4.4. *Results with Non-sliding Contacts*

Of the materials tested, all which contained any copper or silver (625 alloy, PGS, 30% Ag-Au, 20% Pd-Ag) gave rise to high contact resistance in many cases. No doubt this was due to the formation of thin oxide or sulphide films. The same materials gave somewhat better but still poor results when used against pure gold.

Materials of the platinum group were much better, nearly always giving a mean contact resistance between 1 and 10 ohms. Resistances of this order can be explained by tunnel effect conduction (Appendix 2) through a film of 8 to 9 Å total thickness. The oxygen molecule is 2·7 Å across and 3·94 Å long, and a possible explanation would seem to be that oxygen molecules tend to be arrayed on end on platinum surfaces in a monomolecular adsorbed layer.

Gold versus gold contacts were the most satisfactory combination, almost all the contacts tested giving a mean resistance below 1 ohm. According to Holm,[1] freshly prepared gold surfaces acquire a monomolecular layer of oxygen atoms lying flat, after about two days exposure to air. The tunnel effect resistance for a 5·4 Å film on contacts of the type tested would be less than 0·1 ohm. These contacts tended to stick slightly at the start of a test, but the effect became negligible after a few days. In spite of these good results, it was later found necessary to abandon non-sliding contacts altogether because tests using larger numbers of choppers proved them insufficiently reliable.

4.5. *Results with Sliding Contacts*

Contacts in which both surfaces were of 625 alloy were quite unsatisfactory, many pairs giving mean resistances of 10 to 1000 ohms after one or two months. The waveform was usually finely striated and it is presumed that a resistive film is formed, possibly of copper oxide, which breaks down in many places, possibly embedding itself in the parent metal. Sliding contacts of this alloy developed high resistance more rapidly than non-sliding contacts, an effect which may be explained by the concept of frictional oxidation outlined in Appendix 4.

A few choppers were made having the sliding contacts of pure hard-drawn gold. As might be expected, however, all these operated erratically due to seizure between the contacts. It is in fact well known that cold welding takes place if two gold surfaces are brought together with a sliding action.

Other combinations giving poor results were Au-Ag versus Au-Ag (high resistance in every test), Pd-Ag versus Ir-Pt (mean resistance below 2 ohms, but high peak values), and pure gold versus 625 alloy.

Several combinations, however, gave good results, the following in particular being uniformly satisfactory:

All Ir-Pt versus Pt combinations.

PGS versus Au.

15% Ir-Pt versus Au.

A general impression gained from the observation of many contacts over long periods was that combinations of pure hard-drawn gold, sliding against a harder material, itself not subject to serious film formation, were the most reliable. The combination finally chosen was PGS versus gold, the choice being made largely because these two materials when used together develop a low thermal e.m.f. It is probable that platinum alloy versus gold combinations would be equally good from the point of view of contact resistance. Recent tests have shown that the performance would also be satisfactory in respect of thermal e.m.f.s.

Although it might be expected that pure gold would wear rapidly, this does not seem to be the case. Tests on the PGS—gold combination extending over three years showed no measurable change in the waveform.

5. Effects of Hermetic Sealing

5.1. *Test Conditions*

A total of 162 choppers, containing 648 contact pairs, were constructed in seven batches sealed in three different ways, and operated continuously for periods up to 26 weeks.

Batch A choppers (32) were enclosed in impact-extruded aluminium cans, sealed to the top and bottom bakelite mouldings by Neoprene rubber "O" rings.

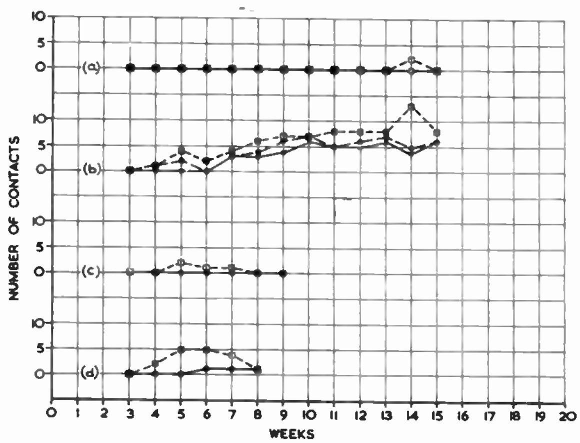
Batch B and C choppers (59) were enclosed in similar cans, but each "O" ring was replaced by three 0·030 in. Porvic washers, 5 micron grade, sealing along their inner and outer edges by slight radial interference with the can and bakelite mouldings. The washers were free to float axially a little, thus having their larger faces free to transmit air.

Batch D, E, and F choppers (71) were again similarly enclosed, but in this case the seals were omitted entirely so that the choppers could "breathe" very freely.

The peak contact resistance of every contact pair was assessed weekly at an applied voltage of 10 mV, in terms of the series resistance R_p which gave a visually perfect oscilloscope trace. For the rest of the time no voltage was applied to any of the contacts. Results were assessed on a statistical basis by plotting the number of sliding and non-sliding contact pairs in each batch having values of R_p equal to or exceeding 100 ohms, 1 kilohm, and 10 kilohms. The results are presented in Figs. 4–6, and indicate at once how many contacts in each batch fall either side of any particular resistance criterion. The peak contact resistance in each case is of the order $R_p/100$.

5.2. *Discussion of Results*

In choppers sealed with "O" rings (Fig. 4) nearly all the sliding and non-sliding contacts required an R_p of at least 100 Ω after 6 to 10 weeks. Some 25% of sliding and 15% of non-sliding contacts required a value of 10 kΩ or more. This represents a peak contact resistance exceeding about 100 Ω, and would not be tolerable in many circuits. Removal of the "O" rings after 15 weeks gave some immediate improvement, but this was probably due to mechanical disturbance and was not maintained.



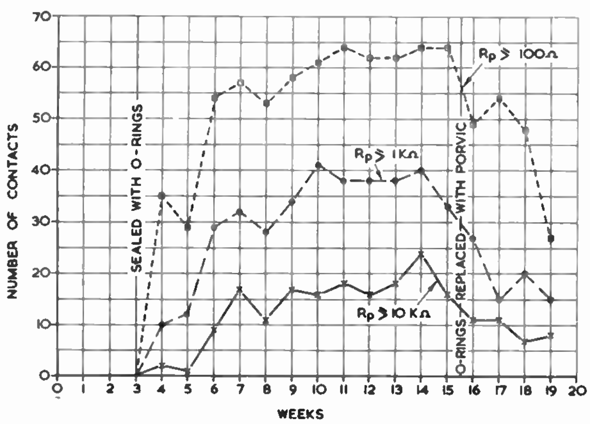
(*a*) Batch B: 30 choppers, 60 sliding contact pairs.
(*b*) Batch B: 30 choppers, 60 non-sliding contact pairs.
(*c*) Batch C: 29 choppers, 58 sliding contact pairs.
(*d*) Batch C: 29 choppers, 58 non-sliding contact pairs.

Fig. 5. Contact resistance of choppers with porous seals.

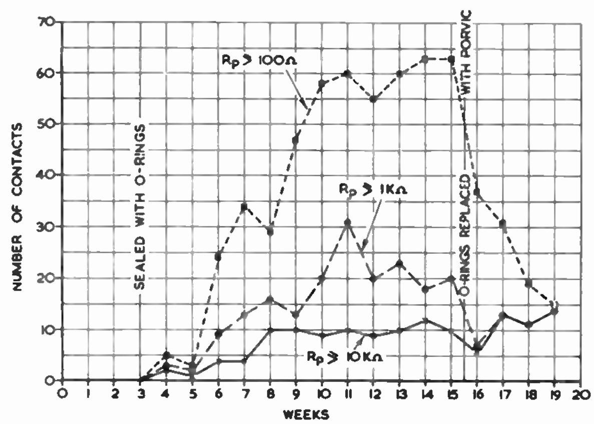
It is presumed that volatiles emanating from the bakelite base or top, or from the "O" rings, or from some other organic constituent of the choppers (enamel on the wire used to form the coil, polythene sleeving, elastic polythene tape, etc.) in some way form a resistive film on the contact surfaces which is not broken down by the amount of sliding present.

Choppers sealed with porous p.v.c. seals (Fig. 5) gave strikingly better results, as did those not sealed at all (Fig. 6).

In these cases, the sliding contacts gave results which can be regarded as 100% acceptable. In most

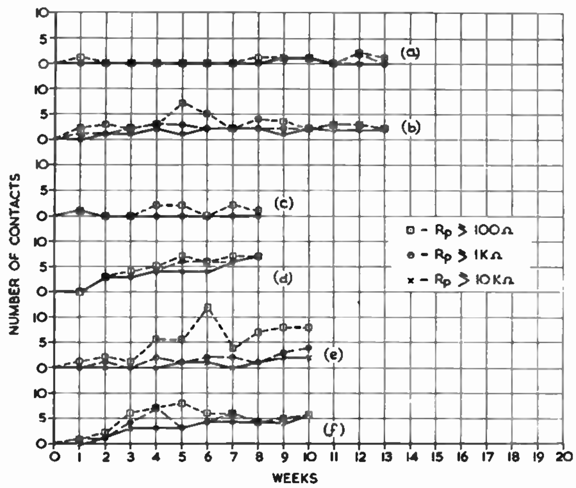


(*a*) Batch A: 32 choppers, 64 sliding contact pairs.



(*b*) Batch A: 32 choppers, 64 non-sliding contact pairs.

Fig. 4. Contact resistance of choppers with O-ring seals.



(*a*) Batch D: 20 choppers, 40 sliding contact pairs.
(*b*) Batch D: 20 choppers, 40 non-sliding contact pairs.
(*c*) Batch E: 21 choppers, 42 sliding contact pairs.
(*d*) Batch E: 21 choppers, 42 non-sliding contact pairs.
(*e*) Batch F: 30 choppers, 60 sliding contact pairs.
(*f*) Batch F: 30 choppers, 60 non-sliding contact pairs.

Fig. 6. Contact resistance of unsealed choppers.

of the few cases where slight contact resistance developed, it was rapidly cleared by the rubbing action.

Non-sliding contacts were also improved by the elimination of air-tight sealing. However, there was still a failure rate ($R_p \geqslant 10$ kΩ) of the order of 2 to 15% according to batch. A feature of these contacts is that occasional failures occur after many weeks of satisfactory operation, and are not self-correcting. The results obtained with non-sliding contacts are clearly not acceptable.

6. Conclusions

Tests carried out on a large number of mechanical choppers showed that:

(1) For complete reliability, the contacts must operate with at least a slight sliding action in order to break down thin non-conducting films on the contact surfaces. The sliding action must, however, be small enough to cause negligible wear.

(2) Of several combinations of contact materials giving low contact resistance, pure gold versus PGS alloy, and pure gold versus iridium-platinum alloys, were found to be particularly satisfactory.

(3) In designs using materials having an organic base (bakelite, etc.), the choppers must be sealed in a manner which allows them to breathe, since hermetic sealing does not allow the escape of volatile compounds liable to give rise to non-conducting films on the contact surfaces.

7. Acknowledgments

The directors of George Kent Ltd. are thanked for giving their permission for this paper to be published.

8. Appendix 1: Constriction Resistance

Even with careful grinding and polishing it is difficult to produce surfaces which are flat to better than 10^{-5} cm. Thus when two practical surfaces are brought together, they first touch at a few high points or asperities only.

Even light loads cause these asperities to deform first elastically, and then plastically until their total area is such that it can support the load. The total area of contact is then[1, 2]

$$A = \frac{W}{P_m} = \frac{W}{H} \simeq \frac{W}{3Y} \qquad \ldots\ldots(1)$$

where W = the load,
P_m = the mean pressure at the points of contact,
H = the hardness measured with a spherical indenter, and
Y = the elastic limit in tension.

If the two materials have different properties, it is those of the softer material which matter. If the material is capable of work hardening, Y may be taken as the elastic limit for the work-hardened material.

The area of apparent contact, due to elastic deformation of the bulk material, may be similar to that given above or much greater and, for the case of two crossed cylindrical surfaces of radius r, the radius of the area of apparent contact is

$$a = 1{\cdot}1\left\{\frac{Wr}{2}\left(\frac{1}{E_1}+\frac{1}{E_2}\right)\right\}^{\frac{1}{3}} \qquad \ldots\ldots(2)$$

where E_1 and E_2 are Young's Moduli for the two materials and W is the load.

Any current flowing from one contact to the other is restricted to the small areas of contact, and this gives rise to a "constriction resistance"[1] between the contacts. For two perfectly clean metal surfaces which touch over a single circular area of radius a, the value is[1]

$$R = \frac{\rho_1+\rho_2}{4a} \qquad \ldots\ldots(3)$$

where ρ_1 and ρ_2 are the resistivities of the materials.

If the surfaces touch at a number of widely spaced circular areas, the conductivities of these constrictions can be added provided that each individual area is known. If they touch at a number of closely spaced areas, the spacing must be known as well. It is useful to assume, however, that contact in fact takes place over a single circular area, since this gives an approximate estimate of constriction resistance which may be somewhat high, i.e. pessimistic.

On this basis, the constriction resistance between two hard-drawn pure gold wires, with a load of 5 gm, is in the order of 2×10^{-3} ohms, while that for harder or more resistive materials may be an order or so higher.

The effect is clearly not significant in itself to the design of choppers, but is of interest since it indicates that the contact resistances found in practice must have some other cause.

9. Appendix 2: The Tunnel Effect

In air, the noble metals and their alloys carry very thin surface films, usually of oxygen, adsorbed on their surfaces. Although only one or two molecules thick, these films prevent the cold welding which would otherwise take place when two pieces of metal are brought into contact. The conductivity of these films is fortunately much better than would be expected from conductivity measurements on thicker films. The explanation lies in the tunnel effect, whereby electrons are transmitted through rather than over potential barriers whose thickness is of the same order as the electron wavelength.

Expressions for the resistance of such films have been given by Holm[1] and others in terms of their area, thickness and the work function for electron emission of the surfaces.

Table 3 gives calculated values of contact resistance against film thickness for a contact area of 10^{-6} cm^2 (hard-drawn gold contacts with a load of 10 gm) and a work function of 5 eV.

Table 3

Contact Resistance *versus* Film Thickness

Film Thickness Å	Contact Resistance, ohms
6	0·1
7	1·0
8	10
9	10^2
10·5	10^3
11·5	10^4

It is clear that even a very approximate measurement of contact resistance allows the film thickness to be estimated quite closely.

10. Appendix 3: The Coherer Effect

If the voltage is increased across a thick tarnish film separating two contacts, a point is reached where the film breaks down and a bridge of metal is formed between the contacts. The breakdown occurs when the electrostatic field is sufficient to accelerate electrons through the film lattice in spite of collisions, and the breakdown voltage is roughly proportional to the thickness of the film. Initially the metal bridge is molten,[4] but it rapidly grows to a size depending on the current capacity of the circuit. It then solidifies, its temperature remaining near the melting point. Thus the voltage across the contacts after the film is punctured is approximately equal to the melting voltage for the contact material in question, i.e. between 0·1 and 1·0 V (0·4 V for gold).

The coherer effect is responsible for good electrical contact in commutators, and often comes into play in plug and socket connections, relays, etc., when the circuit voltages are sufficiently high. The "wetting" by d.c. of contacts carrying small a.c. signals is a deliberate application of the coherer effect.

11. Appendix 4: Frictional Oxidation

According to this concept, suggested by Holm[1] friction may loosen oxygen atoms near the surface of an oxide film and cause fissures in it. This exposes deeper layers to air and so causes further oxidation.

Tests on choppers with 625-alloy contacts lend support to the theory.

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GRADUATESHIP EXAMINATION—NOVEMBER 1960—PASS LISTS

This list contains the results of all successful candidates in the November Graduateship Examination. A total of 399 candidates entered for the Examination which was held at fifty-nine centres.

LIST 1: The following candidates have now completed the Graduateship Examination and thus qualify for transfer or election to Graduateship or a higher grade of membership.

ADEBOYEJO, Michael Oluseyi (S) *London, W.9.*
ANDERSON, Edward Philip Talbot (S) *Cardiff.*

BENNETT, Wilfred (S) *Stoke-on-Trent.*
BRUNSDON, Graham Paul (S) *Brentwood.*
BUMFORD, Brian Arthur *Reading.*

CHITTY, Arthur Richard *Preston.*
CURLEY, Michael Joseph Colum (S) *Evesham.*

DAVIES, William Peter (S) *Luton.*
DIAS, Cyril Francis (S) *Kerala, India.*
DUTTA, Subal Chandra (S) *Kanpur.*

FARUQI, Muzeffor Hussain Shah (S) *Karachi.*
FERLA, John Anthony *Chippenham.*

GIBBONS, Geoffrey Frederick (S) *Southampton.*
GOVINDAKRISHNAN, Tirunilayi Krishnan (S) *Madras.*
GUPTA, Makhanlal (S) *Agra.*

HO, Kwok Ki (S) *Hong Kong.*
HOSANGDI, Rabindranath Radhakrishna (S) *Bombay.*

IBRAHIM, Tipu Mohamed (S) *Bangalore, India.*

KEOWN, Douglas Grierson *East Kilbride.*
KING, John (S) *Ilford.*

LEE, Han Chi (S) *Hong Kong.*

McLEAN, Donald (S) *Henlow.*
MARSHALL, Laurel Everleigh (S) *Kingston, Jamaica.*
MUNROE, Duke Gray (S) *London, S.W.17.*

ONI, Adelegan Omofadesola (S) *London, S.E.27.*
ONIANWA, Christopher Afamefune (S) *London, N.19.*

RAI, Jagjit (S) *Bombay.*
RAMSAY, James *Reading.*
RING, Hans Chanan (S) *Givatayim, Israel.*

SABBAH, Prosper Benjamin (S) *Kfar-Ata, Israel.*
SARGOOD, Alan Richard (S) *Southampton.*
SHARMA, Gulzari Lal (S) *Trimulcherry, India.*
SMITH, Alan (S) *Evesham.*

TALWAR, Satish Kumar (S) *Agra, India.*

UNNIKRISHNAN, Kartha (S) *Ernakulam, India.*
USMAN, Mirza Mohd (S) *Bahrain, Persian Gulf.*

VENKATESWARAN, K. (S) *Madras, India.*
VOVIDES, Andreas Christou (S) *Limassol, Cyprus.*

WALTER, Robert William (S) *Leicester.*
WIGGINS, John (S) *London, W.2.*

LIST 2: The following candidates have now satisfied the requirements of Section A and are now eligible to enter for Section B.

ALLINSON, John Michael (S) *Birmingham, 20.*
AMIRTHALINGHAM, Saravanamuthu (S) *Trincomalee, Ceylon.*
AMPAH, Stephen Ekow (S) *London, N.W.2.*
ANTIGHA, Arthur Robert Edet (S) *Lagos, Nigeria.*

BARDOS, Peter Andrew *London, W.2.*
BATRA, Bhim Sen (S) *Saharanpur, India.*
BEN-YOSEF, Michael (S) *Givatayim, Israel.*
BHANU PRAKASH, Bangalore Venkatadri (S) *Bangalore, India.*
BUCHNER, Otto Josef (S) *Rijswijk, Holland.*
BOWMAN, Alan Michael (S) *Dartford.*
BRAVINSKY, Gary (S) *London, N.W.3.*

CALLENDER, Peter Charles (S) *Auckland, New Zealand.*
CHAPMAN, Derek James (S) *London, N.W.11.*
CLARK, Anthony Harold (S) *Southsea.*
CROMPTON, Craig Pickop *Stroud.*
CURTIS, Anthony Reginald (S) *Reading.*

DAVIS, John Graham (S) *Norwich.*
DIXEY, Graham Edward (S) *London, N.W.4.*
DOCTORS, Michael Stephen (S) *London, E.17.*

EZE, Victor Chukwuemeka (S) *London, N.7.*

GARTHWAITE, Frank George Leslie (S) *Earlswood.*
GHOSE, Purushottam (S) *Aldermaston.*
GIBSON, George Arthur (S) *Weston-super-Mare.*
GOPINATHAN, Thonnangamath (S) *Poona, India.*
GOVINDASWAMY, Gunti (S) *Chandra Giri, India.*
GROOSHKEVITS, Yoram (S) *Magdiel, Israel.*
GROVES, Charles Morley (S) *Bexhill-on-Sea.*

HAIZEL, Kwamina Bainyi (S) *London, W.9.*
HANCOCK, Donald Michael (S) *Romsey.*
HARRIS, Herbert Arthur (S) *Johannesburg, South Africa.*

KAOS, Ioannis Nicolaou *London, E.9.*
KAUSHAL, Ram Sarup (S) *Gurgaon, India.*
KEEBLE, Ronald Sidney (S) *Holmer Green, Bucks.*

KUMAR, S. K. L. (S) *Kanpur, India.*
KWAPNIEWSKI, Jerzy Josef (S) *London, W.11.*
KWAWUKUME, Oscar Atsu (S) *London, S.W.2.*

LAVENDER, Derek Charles (S) *Nuneaton.*

MALONE, Colin Terence (S) *Hayes, Middx.*
MARTIN, Joseph William (S) *New Delhi, India.*
MICHAEL, Elias *London, N.19.*
MINOGUE, Jeremiah (S) *Cahirciveen, Eire.*
MOSLEY, John Malcolm (S) *London, S.W.2.*

NABI, Tajul Islam Mohammad Nurun (S) *Karachi, Pakistan.*
NAGARAJA RAO, Burki (S) *Bangalore, India.*
NEWMAN, Edward Victor (S) *H.M.S. Victorious, London.*
NEWRICK, Roy William (S) *B.F.P.O. 180.*

PIRES, Harold George (S) *London, S.E.19.*

RANGANATHAN, T. Muthuswami (S) *London, W.1.*
RATTAN, Avtar Singh (S) *Nairobi, Kenya.*
ROBINS, John Keith (S) *London, N.W.2.*

SCURRAH, Robert Eric (S) *London, S.W.16.*
SEENEY, Gordon William (S) *B.F.P.O. 10.*
SON HING, Cecil Bickford (S) *London, W.8.*

TAKKAR, Sushil Kumar (S) *Kerala, India.*
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WEATHERILL, William Robert (S) *Blewbury, Berks.*
WEENINK, Martinus Cornelis *Rio Canario, Neth. Ant.*

YEONG, Kum Tien (S) *Singapore.*
YIP, Seck Weng (S) *Singapore.*

(S) denotes a Registered Student

U.D.C. 621.376.203

Elimination of Even-order Modulation in Rectifier Modulators

By

Professor D. G. TUCKER,
D.Sc. (*Member*)†

Summary: Previous analytical treatments of rectifier modulator circuits have usually assumed that the time-varying-resistance function of the rectifiers is a square wave. Differences in behaviour when the function is not only not square, but also contains even-order harmonics of the carrier frequency, are here discussed. Among other and more general results, it is shown how even-order modulation products can be eliminated altogether in the ring, series and shunt types of modulator provided that (*a*) the carrier waveform comprises only odd harmonics and (*b*) the external circuit impedance is a pure resistance R at all odd-order modulation-product frequencies, and can be related to the rectifier resistance/voltage characteristic, $r(V_c)$, so that $R^2 = r(+V_c).r(-V_c)$. This condition coincides with that for minimum conversion loss.

List of Symbols

ω_p angular frequency of "carrier" or local-oscillator.
ω_q angular frequency of input signal.
$r(t)$ time-varying resistance of rectifier.
$g(t)$ time-varying conductance of rectifier $= 1/r(t)$.
Z impedance, Y admittance, R resistance, G conductance — of external circuit (i.e. signal source and load suitably combined: in series in series modulator, in parallel in shunt-modulator).
R_S resistance of signal source.
R_R resistance of receiving circuit or load.
$\phi(t)$ modulating function.

1. Introduction

Even-order terms are a matter of importance in the theoretical aspects of rectifier modulators as well as in the more practical considerations. The latter are, of course, obvious; if a modulator produces even-order modulation products in its output circuit (say $l\omega_p \pm \omega_q$, where ω_p = angular frequency of the carrier, and ω_q = angular frequency of the signal, l being an even integer) then, for example, the realizable bandwidth of an upper sideband $\omega_p+\omega_q$ is restricted by the existence of another band $2\omega_p-\omega_q$. The importance in theoretical studies is more abstruse, but arises mainly through the disproportionate complication introduced into the modulator equations; thus

(i) When the system is regarded as linear with a time-varying resistance element $r(t)$ to represent the rectifier circuit (controlled entirely by the carrier), then even when $r(t)$ contains only odd-order harmonics of the carrier, even-order modulation products are, in general, produced; and these cause the equations to be very complicated and almost impossible to solve. If, however, even-order products can be eliminated—this can, for example, be achieved by making the external circuit impedance a constant resistance at all odd-order product frequencies, and at the same time making $r(t)$ a square wave—then the equations immediately become easy to solve. This has been adequately discussed in recent papers.[1, 2]

(ii) When $r(t)$ itself contains even-order harmonics the number of terms in the equations is nearly doubled unless even-order modulation products are absent—but even then the equations remain difficult to solve. Moreover, if the even-order harmonics in $r(t)$ arise because the carrier waveform has unequally-spaced zeros—e.g. a square-type wave with unequal "mark" and "space" intervals—then, not only can even-order modulation products not be eliminated, but no longer can the ring modulator be represented by the same set of equations as the series and shunt-modulators. These matters are more fully discussed in ref. 3.

It is therefore important to know the circumstances in which even-order modulation products can be eliminated. This paper presents an examination of this problem for ring, series and shunt modulators (the various circuit arrangements of which are thought to be well-known in view of the adequate literature on them) under the following conditions:

(*a*) for the ring modulator, the load impedance Z_R (see Fig. 1) is a constant resistance at all frequencies which occur in its part of the circuit.

(*b*) for the series and shunt modulators, the impedance Z in the single-loop equivalent circuit (see Fig. 2)—i.e. signal-source and load impedances combined, in series in the series modulator and in parallel in the shunt modulator—is a constant resistance at all frequencies which occur in the effective circuit.

† Electrical Engineering Department, University of Birmingham.

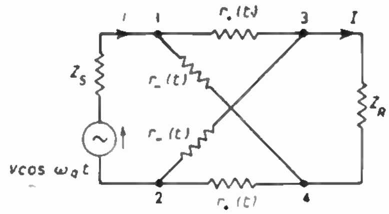


Fig. 1. Effective circuit of ring modulator.

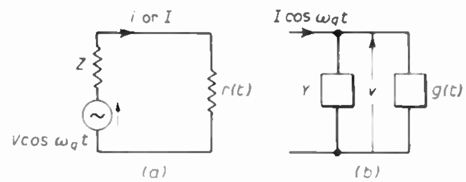


Fig. 2. Effective circuit of series and shunt modulators. (*a*) with e.m.f. signal-source. (*b*) with current signal-source.

(*c*) there are no unbalance effects, i.e. all rectifiers in the circuit are identical. Such effects are discussed in ref. 4.

(*d*) the circuits are linear, i.e. the resistance function $r(t)$ is unaffected by the signal amplitude.

2. Types of Waveform of Carrier and of $r(t)$ to be considered

In practice, even-order terms enter into the Fourier expansion of $r(t)$ due to two causes:

(i) when the carrier voltage is not a square wave, although "symmetrical",† even-order terms occur in $r(t)$ because the resistance/voltage characteristic of the rectifier is not skew-symmetrical about the ordinate at $V_c = 0$, i.e.

$$r(+V_c) - r(0) \neq r(0) - r(-V_c) \qquad \ldots\ldots(1)$$

and

(ii) when the carrier voltage is of square-wave type, but has unequal "mark" and "space" intervals, even-order terms are introduced into $r(t)$ due to the error in switching time.

Figure 5 illustrates case (i). The rectifier resistance is plotted as a function of the instantaneous carrier voltage—i.e. the function $r(V_c)$. Then using the carrier voltage waveform as shown, the resistance is obtained as a function of time, i.e. $r(t)$. The carrier waveform is considered to be at least half-cycle-symmetrical, and so to contain no even-order harmonics, when

$$V_c(\omega_p t) = -V_c(\omega_p t + \pi) \qquad \ldots\ldots(2)$$

It is clear that when V_c is quarter-cycle-symmetrical, then $r(t)$ contains harmonics (including even-orders) of cosine type only, as illustrated for a waveform $\phi(t)$ in Fig. 6, where only the fundamental and second harmonic components are shown. When V_c is only half-cycle-symmetrical, harmonics of sine type also enter into $r(t)$.

† "Symmetrical" is used to include quarter-cycle-symmetrical and half-cycle-symmetrical waves; the former type may be defined as being skew-symmetrical about its zeros and truly symmetrical about the points midway between zeros, while the latter has positive and negative half-cycles identical except for reversal of polarity. These waves contain only odd-order harmonics.

Now it is clear from Fig. 3 that in a ring modulator the carrier voltage V_c across the rectifiers must necessarily be symmetrical if the carrier e.m.f. is itself symmetrical—the latter will usually be sinusoidal, so that V_c is quarter-cycle-symmetrical. But in a shunt or series modulator this is not necessarily so, since the rectifier resistance does not give a symmetrical load to the carrier generator. Therefore, in a single modulator, the voltage V_c across the rectifiers will not be symmetrical unless the carrier source impedance is practically zero. The larger voltage developed across the back resistance of the rectifiers may have an advantage in respect to non-linear distortion and overload, but it is common practice to obtain a symmetrical V_c by feeding two modulators in opposite connection, as shown in Fig. 4.

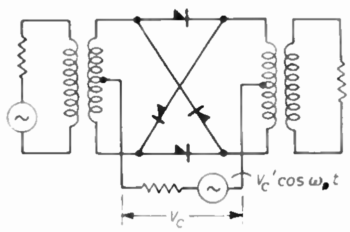


Fig. 3. Carrier circuit of ring modulator.

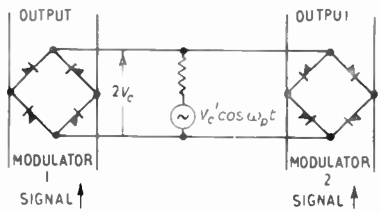


Fig. 4. Carrier circuit of a pair of shunt modulators arranged to give symmetrical carrier voltage across rectifiers.

Figure 7 illustrates case (ii). It is convenient to separate the error waveform due to the unequal mark and space, as shown at (*b*). It can be seen by inspection that the additional components introduced are, firstly, some cosine odd-order harmonics of ω_p which oppose those in the true square wave, and, secondly, some cosine even-order harmonics.

3. Conditions for the Absence of Even-order Modulation Products in the Ring Modulator

It has been shown by Kruse[5] that in the ring modulator, whatever the nature of Z_S and Z_R, but provided the carrier waveform contains only odd-order harmonics—i.e. is at least half-cycle-symmetrical—then only odd-order modulation products ($n\omega_p \pm \omega_q$, when n is an odd integer) are produced in the output circuit, and only even-order products in the input circuit. It is, indeed, this separation of odd- and even-order products which enables the ring modulator to be represented by the same equations as the series and shunt modulators.[1] Since even-order products are already absent from the output circuit, the practical interest in their elimination from the input circuit is small, but the theoretical importance of this is considerable. We see that the condition for absence of even-order products must be that the input impedance (Z_i) of the modulator[2] (i.e. that seen looking into terminals 1, 2 in Fig. 1) is a constant pure resistance over the whole carrier cycle. The input loop then has only constant-parameter elements, and the only current or voltage components which can exist must be those at the frequency of the applied signal. We have already assumed the load Z_R to be a constant resistance (R_R), so that the conditions for Z_i to be a constant resistance (i.e. constant with time and with frequency) are as follows:

(i) If $r(t)$ is a square-wave, then Z_i will necessarily be a constant resistance, since the effect of the carrier is merely to switch the polarity of the circuit; there is no reactance to store energy, so that the input resistance is unaffected by the switching.

(ii) If $r(t)$ is not a square-wave, then by the theory of iterative networks, Z_i will be a constant resistance (equal to R_R) if at all values of t,

$$r_+(t).r_-(t) = R_R^2 \qquad \ldots\ldots(3)$$

Since the carrier circuit is symmetrical, this is the same as specifying that

$$r(+V_c).r(-V_c) = R_R^2 \qquad \ldots\ldots(4)$$

where r is expressed as a function of V_c as in Fig. 5. If $r(V_c)$ contains any constant part (r_d) which prevents eqn. (4) being fulfilled as it stands, or requires the addition of a constant resistance r_d to enable eqn. (4) to be met, then this constant part can be removed into the terminations (by the use of a well-known lattice network theorem),† so that the condition now becomes:

$$[r(+V_c)\pm r_d][r(-V_c)\pm r_d] = (R_R \mp r_d)^2 \qquad \ldots\ldots(5)$$

These conditions (i) and (ii) are therefore the conditions for even-order products to be absent in the ring modulator. Clearly R_R need not be physically a constant pure resistance, and it will, under steady-state conditions, be sufficient for Z_R to have the value R_R only at the frequencies of all odd-order modulation products; it obviously cannot matter what value Z_R takes at frequencies which do not occur in the circuit.

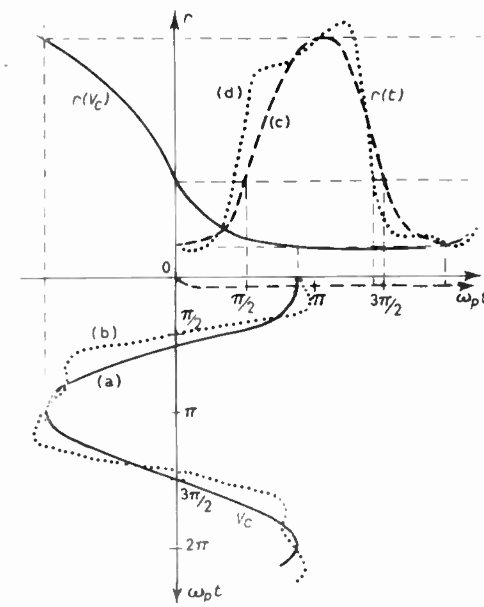


Fig. 5. Derivation of $r(t)$ containing even harmonics of ω_p from (*a*) quarter-cycle-symmetrical carrier voltage, (*b*) half-cycle-symmetrical carrier voltage. Neither (*a*) nor (*b*) contains even harmonics. Curve (*c*) is derived from (*a*), and (*d*) from (*b*).

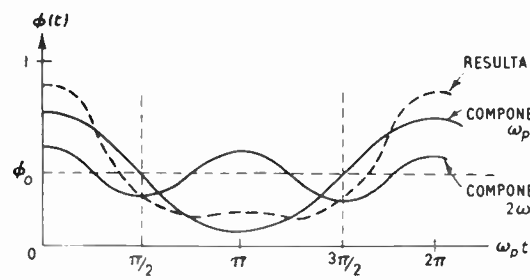


Fig. 6. Illustrating how the lack of symmetry obtained in $\phi(t)$ is produced by cosine components at even-order harmonics of ω_p.

It should be noted that rectifiers can often have their resistance (i.e. dV_c/di) represented with a fair degree of accuracy as an exponential function of voltage,[7] thus

$$r = a\exp(-bV_c)+r_d \qquad \ldots\ldots(6)$$

† A constant shunt component of the rectifier resistance can also be removed in this way, and leads to the same conductance relationship as obtained in eqn. (19) for the series and shunt modulators.

This fits the requirement of condition (ii) very well, since eqn. (5) is met if R_R is chosen so that

$$R_R + r_d = \sqrt{a \exp(-bV_c).a \exp(+bV_c)} = a \quad \text{......(7)}$$

and the input resistance is then $R_R + 2r_d$.

It is interesting that the condition (4) for absence of even-order modulation products coincides with the condition for minimum conversion loss. The Appendix discusses conversion loss in more detail.

When the carrier waveform is of the type of Fig. 7, with unequal mark and space durations, then it is obvious that the output loop contains even-order modulation products whether they are eliminated from the input loop or not. This is most readily seen by considering the modulating function. This is defined[7] as the reciprocal of the insertion loss of the modulator expressed as a function of time—or more conveniently for present purposes as a harmonic series with fundamental angular frequency of ω_p. The output of the modulator is therefore proportional to the applied signal multiplied by the modulating function. If the modulating function contains even-order harmonics, as it clearly must do with a carrier like that of Fig. 7, then there must be even-order modulation products in the output.

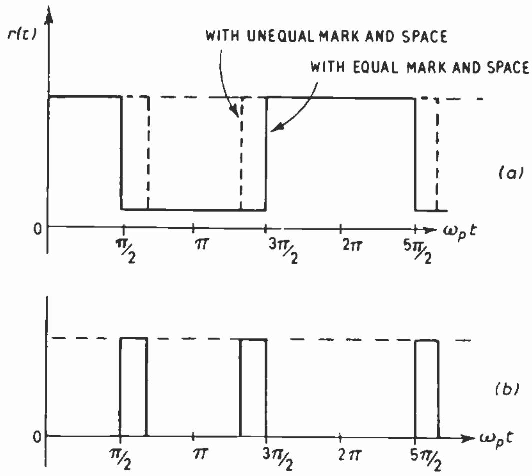


Fig. 7. (*a*) Square-wave carrier waveform, or $r(t)$, with unequal "mark" and "space". (*b*) Waveform of error between wave with unequal mark and space, and true square-wave.

4. Conditions for the Absence of Even-order Modulation Products in the Series and Shunt Modulators

It is now most convenient to consider the problem in terms of the modulating function throughout, since the question of a constant-impedance input loop does not arise, and there is no separation between input and output circuits. If the modulating function contains no even-order harmonics of the carrier frequency then clearly there will be no even-order modulation products in the circuit. It is evident immediately that with a carrier waveform of the unequal mark and space type shown in Fig. 7, even-order products will always be produced. But it must be emphasized that with these circuits a symmetrical carrier waveform is not always essential for the elimination of even-order products. For example, lack of symmetry due to the unsymmetrical loading provided by a single series or shunt modulator can be allowed for, as discussed later in this section.

The modulating function of the series modulator is easily shown to be

$$\phi(t) = \frac{R}{R + r(t)} \quad \text{......(8)}$$

while that of the shunt modulator is

$$\phi(t) = \frac{r(t)}{R + r(t)} = 1 - \frac{R}{R + r(t)} \quad \text{......(9)}$$

where R is the combined value (i.e. the purely resistive value of Z in Fig. 2) of the source and load impedances, Z_S and Z_R respectively.† Clearly the conditions for absence of even-order harmonics in these two modulating functions must be the same, so only (8) will be considered further.

Now this function $\phi(t)$ will be of the same general shape as the curve of $r(t)$ in Fig. 5 (*d*), i.e. entirely positive and made up of even- and odd-order harmonics. The condition for the absence of even-order modulation products is that $\phi(t)$ should contain no even-order harmonics. On the basis of eqn. (2) this condition may be expressed thus:

$$\phi(t) - \phi_0 = \phi_0 - \phi\left(t + \frac{\pi}{\omega_p}\right) \quad \text{......(10)}$$

where ϕ_0 is the mean height of $\phi(t)$ and is not, in general, the same as $\phi(0)$. If we assume that the carrier waveform is symmetrical—by the use of an arrangement such as that of Fig. 4—then

$$V_c(t) = -V_c\left(t + \frac{\pi}{\omega_p}\right) \quad \text{......(11)}$$

so that the condition (10) becomes

$$\phi(+V_c) - \phi_0 = \phi_0 - \phi(-V_c) \quad \text{......(12)}$$

which may be written

$$\phi(+V_c) + \phi(-V_c) = K \quad \text{......(13)}$$

where K is a constant independent of V_c. Using eqn. (8), this becomes

$$\frac{R}{R + r(+V_c)} + \frac{R}{R + r(-V_c)} = K \quad \text{......(14)}$$

† Note that, strictly speaking, no restrictions are placed on Z_S and Z_R individually, so long as the combined value is a pure, constant resistance.

which can be re-arranged as

$$\left[r(+V_c)+R\left(1-\frac{1}{K}\right)\right]\left[r(-V_c)+R\left(1-\frac{1}{K}\right)\right]=\frac{R^2}{K^2} \quad \ldots\ldots(15)$$

If we put $K = 1$, this becomes

$$r(+V_c).r(-V_c) = R^2 \quad \ldots\ldots(16)$$

If we put $R\,(1-1/K) = \pm r_d$, then (15) becomes

$$[r(+V_c)\pm r_d][r(-V_c)\pm r_d] = (R\mp r_d)^2 \ldots\ldots(17)$$

These conditions are essentially the same as those obtained for the ring modulator (eqns. (4) and (5)), and can be realized in practice with exponential rectifiers.

If the carrier waveform is not symmetrical because a single modulator is used, giving an unsymmetrical load to the carrier, then as the zero-crossings remain evenly-spaced, the method can still be applied by specifying r as a function of time, thus:

$$[r(t)\pm r_d]\left[r\left(t+\frac{\pi}{\omega_p}\right)\pm r_d\right] = (R\mp r_d)^2 \ldots\ldots(18)$$

Even-order products are also clearly absent when $r(t)$ is a square wave, since $\phi(t)$ is then also a square wave.

It may further be argued that when even-order products are absent it cannot matter what value Z takes at even-order-product frequencies. If then eqns. (16)–(18) are taken as specifying a value of R (the rectifier being assumed to have a suitable characteristic), it is clear that R need have this value only at odd-order-product frequencies, and need not be physically a constant pure resistance. This then makes the condition identical with that for the ring modulator where only the odd-order termination (Z_R or R_R) is specified anyway.

It should be emphasized that the conditions discussed are those for the complete absence of even-order products from the input and output circuits. Evidently even-order *currents* can be eliminated by making the *impedances* infinite at all even-order frequencies, and even-order *voltages* can be eliminated by making the *admittances* infinite at all even-order frequencies.

The fact that the condition for the series and shunt modulators can be expressed in the same way as for the ring modulator is not surprising in view of the fact that all these modulators, under the stated conditions of symmetrical carrier waveform, can be represented by the same set of equations.

It is interesting to observe that even-order modulation products cannot be eliminated if $r(t)$ is restricted to odd-order harmonics except in the case of a true square-wave; even-order harmonics in $r(t)$ are generally essential to prevent them occurring in $\phi(t)$.

It is shown in the Appendix that condition (16) for the elimination of even-order modulation products coincides with that for minimum conversion loss when the same rectifiers are used, and the signal source resistance (R_S) and the load resistance (R_R) are made equal.

Finally in this section, it should be pointed out that the alternative representation of the series or shunt modulator in terms of admittances and current source, as in Fig. 2 (*b*), yields by exactly corresponding working the condition for elimination of even-order products in terms of $g = 1/r$, thus

$$[g(+V_c)\pm g_d][g(-V_c)\pm g_d] = (G\mp g_d)^2 \ldots\ldots(19)$$

which may sometimes help the practical realization of the condition, especially in the shunt modulator.

5. A General Class of Modulators with Constant Input Impedance and No Even-order Modulation Products

The case of the ring modulator, which not only could be made to have a constant input impedance, but which also under the same conditions produced no even-order modulation products, is really only a particular case of a general class of modulator circuits. It may be observed that the constant-impedance ring modulator is very closely analogous to the lattice form of Zobel's constant-impedance equalizer networks,[8] which gives an input impedance constant with frequency when the product of series-arm impedance (Z_1) and the crossed-arm impedance (Z_2) is a constant at all frequencies, such that $Z_1Z_2 = R_R^2$, where R_R is the terminating resistance. For the ring modulator, we derived the corresponding condition as eqn. (4), namely $r(+V_c).r(-V_c) = R_R^2$. It now becomes clear that all the other forms of Zobel's networks may be used as constant-impedance modulators. These forms are conveniently summarized by Terman[9] as passive linear non-time-varying networks. One example of a ladder type will suffice to indicate how they may be interpreted as modulators. A more comprehensive study of constant-resistance modulators is being published separately.[10]

Figure 8 shows one of Zobel's ladder networks. This can be converted to a modulator, as far as the transmission path is concerned, as shown in Fig. 9, where a balanced formation is used. It is an essential requirement, if such a circuit is to have constant input impedance, that the carrier voltage must be the same (apart from polarity) across all the rectifiers. Thus the complete modulator, including the carrier circuit, has to be rather more complicated, as shown in Fig. 10. It can be seen that this modulator has a constant input impedance, not only in the simple condition arising from Zobel's rule, but also in the more general case, as stated in eqn. (5), where a constant part, r_d, of the

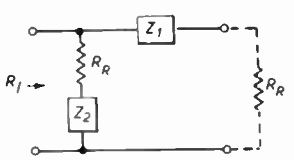
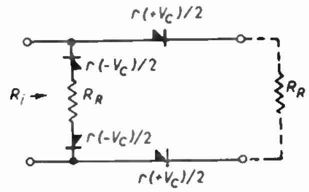


Fig. 8. (*left*) One type of Zobel's constant-impedance ladder networks. $R_i = R_R$ at all frequencies if $Z_1 Z_2 = R_R^2$.

Fig. 9. (*right*) Transmission circuit of modulator analogous to circuit of Fig. 8.
$R_i = R_R$ for all values of V_c if $r(+V_c).r(-V_c) = R_R^2$.



rectifier resistance may be removed to the resistances R_R to enable the requirement to be met.

It may be shown, using the method of Section 4, that condition (5) is also the condition for absence of even-order modulation products. It is curious that condition (5) is *not* the condition for minimum conversion loss, even if $r_d = 0$.

6. Conclusions

From the practical point of view, the most important conclusion is that in a modulator of series, shunt or ring type with a purely resistive rectifier circuit, with a load impedance which has the same purely-resistive value (R) at all odd-order product frequencies (this being source and output load in parallel in the shunt modulator, source and output load in series in the series modulator, but only the output load in the ring modulator), and with a symmetrical carrier waveform, i.e. one containing only odd-order harmonics, there will be no even-order modulation products in input or output circuits when either

(i) the rectifier resistance has a square-wave variation with time, or

(ii) the load resistance, R, and the resistance/voltage characteristic of the rectifiers are such that $r(+V_c).r(-V_c) = R^2$ for all relevant values of the carrier voltage V_c. For the given rectifiers, this condition coincides with that for minimum conversion loss. Any constant part (positive or negative) of $r(V_c)$ which prevents the constant product being obtained may be absorbed into the source and/or load impedances, but the condition for absence of even-order products does not then coincide with that for minimum conversion loss.

7. Acknowledgments

This work was stimulated by questions, work, and suggestions from Mr. J. Tinbergen, a student on the postgraduate course in Information Engineering at the University of Birmingham. The author is grateful also to his colleagues Messrs. J. M. Layton and D. P. Howson for valuable suggestions and stimulating discussion.

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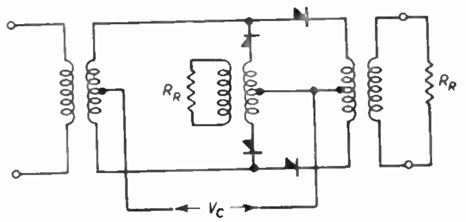

Fig. 10. Complete modulator circuit corresponding to Fig. 9.

9. Appendix: Conditions for Minimum Conversion Loss

It will be assumed that the carrier waveform is symmetrical, and the rectifiers have an arbitrary resistance $r(V_c)$.

9.1. *Ring Modulator*

When the source resistance is R_S and the load is R_R, the modulating function (which is the reciprocal of the insertion loss function and is usually expressed as a time function $\phi(t)$) can be expressed as a function of R_S, R_R and $r(V_c)$ thus:

$$\phi = \frac{(R_S+R_R)[r(-V_c)-r(V_c)]}{(R_S+R_R)[r(-V_c)+r(V_c)]+2R_S R_R+2r(V_c).r(-V_c)} \quad \ldots\ldots(20)$$

If this is differentiated with respect to R_S, it is found that the condition which makes $d\phi/dR_S = 0$ is

$$R_R^2 = r(V_c).r(-V_c) \qquad ......(21)$$

If this condition is met for all relevant values of V_c, then, as has been shown in Section 3, the input impedance of the lattice is a constant resistance, the lattice is iteratively terminated, and in consequence the insertion loss and modulating functions are independent of R_S. This is why it happens that when we put $d\phi/dR_S = 0$ we obtain a condition independent of R_S, instead of an optimum value of R_S.

Since the expression for ϕ is symmetrical in R_S and R_R, i.e. $\phi(R_S, R_R) = \phi(R_R, R_S)$, the condition which makes $d\phi/dR_R = 0$ is

$$R_S^2 = r(V_c).r(-V_c) \qquad ......(22)$$

which is independent of R_R. This is also readily explained in terms of iterative network theory.

In the usual case when R_S and R_R are equal, (say to R), the expression for ϕ becomes

$$\phi = \frac{R[r(-V_c)-r(V_c)]}{[R+r(-V_c)][R+r(V_c)]} \qquad ......(23)$$

and then when $d\phi/dR = 0$ we obtain

$$R^2 = r(V_c).r(-V_c) \qquad ......(24)$$

and the conditions discussed above are obscured.

The modulating function thus has its maximum possible value at every value of V_c—assuming a rectifier resistance law constrained to make the product $r(V_c).r(-V_c)$ a constant over all relevant values of V_c—when *either* termination is equal to the square root of this product. For the particular rectifiers, therefore, the conversion loss is a minimum when *either* R_S *or* $R_R = \sqrt{\{r(V_c).r(-V_c)\}}$ for the range of V_c concerned.

9.2. *Shunt Modulator*

As the modulating function of a shunt modulator, in general, is not symmetrical in the sense that the carrier waveform is symmetrical, we cannot deal with a single value of ϕ as was possible in the ring modulator. But it is possible to say that if $\phi(+V_c)-\phi(-V_c)$ is a maximum for all relevant values of V_c, then the conversion loss is a minimum. Since we wish to regard ϕ as a function of R_S and R_R rather than of V_c while determining optimum conditions, we shall use ϕ_+ and ϕ_- in place of $\phi(+V_c)$ and $\phi(-V_c)$.

It is readily seen that

$$\phi_+ - \phi_- = \tfrac{1}{2}\left[\frac{(R_S+R_R).r(-V_c)}{(R_S+R_R).r(-V_c)+R_S R_R} - \frac{(R_S+R_R).r(V_c)}{(R_S+R_R).r(V_c)+R_S R_R}\right]$$

$$= \tfrac{1}{2}\,\frac{(R_S+R_R)[r(-V_c)-r(V_c)]}{(R_S+R_R)[r(-V_c)+r(V_c)]+R_S R_R+2r(V_c).r(-V_c)+\dfrac{R_S^2+R_R^2}{R_S R_R}\,r(V_c).r(-V_c)} \qquad ......(25)$$

which is very similar to the expression for ϕ in the ring modulator. But the difference is obviously sufficient to prevent the same kind of effect occurring, and we can merely say that as $\phi_+ - \phi_-$ is symmetrical in R_S and R_R (i.e. its value is unchanged if R_S and R_R are interchanged), its maximum value occurs when $R_S = R_R$. Since we wish to refer the result to the equivalent single-loop circuit, it is convenient to say $R_S = R_R = 2R$, so that R is then the single-loop terminating resistance as in Fig. 2.

Then

$$\phi_+ - \phi_- = \tfrac{1}{2}\,\frac{R[r(-V_c)-r(V_c)]}{[R+r(-V_c)][R+r(V_c)]} \qquad ......(26)$$

which apart from the factor $\frac{1}{2}$ is identical with ϕ for the ring modulator with $R_S = R_R = R$. This has a maximum when

$$R^2 = r(V_c).r(-V_c) \qquad ......(27)$$

which is therefore the condition for minimum conversion loss if it holds at all relevant values of V_c.

9.3. *Series Modulator*

Evidently the same reasoning as in (9.2) can be applied to the series modulator, with the same results provided we put $R_S = R_R = \frac{1}{2}R$.

Manuscript received 18th March 1960 (Paper No. 611).

News from the Sections in Great Britain

West Midlands Section

The third meeting of the Section's current programme was held at Wolverhampton College of Technology on 9th November, when Mr. K. C. Johnson, M.A., gave a paper on "Modern Computer Techniques". Confining his remarks to digital computers the author first discussed the fundamentals of operation and then passed to a consideration of early computers using vacuum tubes. Later developments employing transistors were then described. A comparison was made between computers using parallel operation in which the highest speeds are obtained and the serially operating type which have the advantage of using fewer components. The paper concluded with a discussion of future trends, notably the use of tunnel diodes and cryotrons.

For the meeting on 23rd November facilities were again provided at Birmingham University, when a discussion on "The Various Routes to Professional Qualifications in Electronic Engineering" took place with Professor D. G. Tucker, D.Sc. (Member) in the Chair.

Three different methods of qualification apart from taking the Institution's Graduateship Examination were described. These were the University Degree, the Diploma in Technology and the Higher National Certificate.

The general concensus of opinion at the meeting was that the first two of these were, in general, satisfactory. Some concern was expressed, however, about the correlation between the academic and practical work of students engaged in sandwich courses. It was pointed out that such students were visited regularly during their periods in industry by tutors who themselves learned by this means something of the practical application of the more academic studies. The point was also made that most practising engineers did not need a high academic standard and that the time employed in their training might well be better spent in dealing with the more practical aspects of their future work.

In regard to the H.N.C. courses, it was felt that in many cases the standards were too low. Several speakers mentioned the difficulties encountered in trying to find a H.N.C. course with sufficient electronics content to satisfy the Institution's requirements. Against this, it was stated on behalf of the Technical Colleges in the area that a course could not be arranged unless a reasonable number of students could be relied upon to attend, and that there was no way of finding out in advance what the demand for a given course would be. This seemed to be a difficulty which could be surmounted by better liaison between the Colleges and local industry.

D. H. A.

North Eastern Section

At the second meeting of the current session, held in Newcastle-upon-Tyne on 9th November, Mr. A. W. Mews (Associate Member), read a paper on "The Distribution of Sound and Television by Wire".

Mr. Mews began by briefly discussing wired sound distribution systems as an introduction to his main theme—the distribution of television. The factors affecting the design of a system were discussed with particular reference to the influence of cable characteristics and the author then described and illustrated the features of a practical system from the master aerial to the subscriber installation. Reference was made to other wired systems and to the future possibilities of new cable types and transistorized equipment.

South Midlands Section

The place of the electronic rocket in space propulsion was the title of an unusual paper read on 2nd December in Cheltenham by W. A. Scott Murray, Ph.D., of the Royal Radar Establishment.

Dr. Murray explained how simple expressions could be derived for the relationship between momentum, thrust and power in a rocket exhaust. From these results it was shown that two distinct types of rocket motor have application in space flight: the now familiar chemical rocket and the more futuristic electrical machine which will be suitable for long distance work. Finally, performance requirements for some inter-planetary journeys, leading to a possible design for a deep space vehicle were outlined.

East Midlands Section

An exploratory meeting of members resident in the East Midlands area was held on Wednesday, 25th January, at the College of Technology and Commerce, Leicester. It was agreed at the meeting to appoint a Committee to arrange an experimental session of meetings during 1961–2. The Committee will organize four meetings, all of which will be held in Leicester, and if these are sufficiently well supported, the Committee proposes to petition the Council of the Institution for the formation of a Section.

The following members have been elected to the Committee:—

R. L. Duthie, (Associate Member)—*Chairman*
W. J. Stevenson (Associate Member)—*Secretary*
A. B. Clewes, P. G. Curtis, G. B. Miller, D. Reaney and J. A. Tempel (Associate Members) and T. L. Perry (Associate).

Any member who wishes to offer assistance to the Section Committee should write to the *Honorary Secretary*, Mr. W. J. Stevenson, at 77 Beacon Road, Loughborough, Leics.

Waveguide Components

A Survey of Methods of Manufacture and Inspection

By

D. J. DOUGHTY,

D.C.T.(Battersea) (*Associate Member*†)

Summary: This survey describes techniques which are at present used in the manufacture of microwave components of waveguide form, and gives some guidance and discussion on methods of inspection of these components. No specific mention is made of waveguide forms other than the cylindrical and rectangular types in general use, although many of the methods discussed will be equally applicable to other waveguide sections.

Table of Contents

PART 1. MANUFACTURING METHODS

1. Introduction

The method of manufacturing drawn waveguide tube for microwave transmission systems is considered first, followed by a section dealing with electroforming methods, which may be used to produce either standard lengths or bends, hybrids and other complex components. The next section discusses bending, brazing and welding techniques, mainly as applied to the manipulation of drawn tubes.

Sections 5 and 8 are respectively concerned with the application of various machining and casting techniques to the manufacture of waveguide components.

Sections 6 and 7 deal with techniques which have been specifically developed for microwave component manufacture, namely, the building up of waveguide parts by metal spraying, and assembly from pressings, including the "twisted tag" method of self-jigging for dip-brazing.

The manufacture of several different types of flexible waveguide is dealt with in Section 9.

No attempt has been made to give hard and fast recommendations concerning the application of the techniques discussed. Many factors will need consideration before the final decision to adopt a certain

† Electrical Inspection Directorate, Ministry of Aviation, Bromley, Kent.

technique for manufacturing a particular component, e.g. weight or material restrictions, relative costs, electrical performance limits, mechanical complexity, availability of processes, quantity required, application of the finished component, time available, and the designer's experience with the various methods. Thus two identical electrical requirements may produce mechanically dissimilar components, due to considerations under any of the points mentioned above.

2. Drawn Lengths of Waveguide Tubing

In the absence of a British Standard Specification for waveguides, industry generally adheres to the requirements of Defence Specification DEF–5351 for the production of drawn waveguide tubes, a document primarily concerned with standardization for Inter-Service use.[1] The specification details materials, dimensions, internal surface finish and other mechanical parameters, together with information concerning frequency range, attenuation, power rating and cut-off frequency for the dominant (H_{10}) mode in rectangular tubes. It also lists similar information concerning cylindrical waveguide sizes which are under consideration for future standardization.

Present use of drawn cylindrical waveguide is generally restricted to short lengths, e.g. in rotating joints, and although future widespread use in multi-channel links is probable, virtually all commercial production of waveguide tubing is of rectangular form.

Seamless drawn waveguide tube is available in standard lengths varying from 14 ft for size WG8 (4·300″ × 2·150″) to 6 ft for WG26 (0·122″ × 0·061″). WG18 (0·622″ × 0·311″) and larger sizes are generally available in copper, brass or aluminium, while WG20 (0·420″ × 0·170″) and smaller are normally drawn in copper or silver. Copper/silver and brass/silver laminated tubes may also be obtained, the silver laminate covering the inner surface of the tube to a nominal depth of 10% of the tube thickness, with 0·015 in. minimum laminate depth.

Brass and aluminium tubes are re-drawn from standard stock cylindrical tubes conforming with

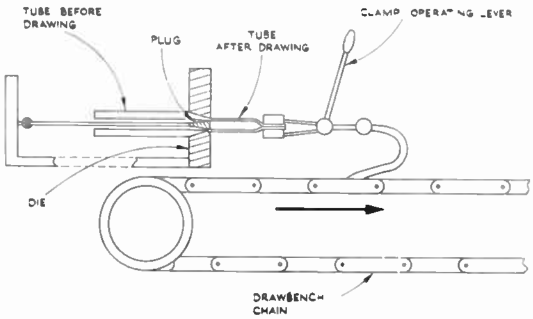

Fig. 1. Arrangement of typical drawbench.

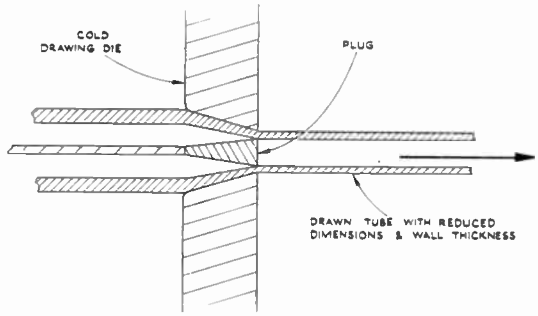

Fig. 2. Section through tube drawing die.

B.S. 2871–CZ.105 for 70/30 brass, B.S. 713 for 90/10 brass and B.S. L54 for aluminium. Copper is pure high conductivity electrolytic to B.S. 2871–C101 or C106, and silver is to commercial standard, nominally 92·5% silver and 7·5% copper. Copper, silver and laminated tubes are usually manufactured from sheet material, using cupping and re-drawing operations.

Of the three standard tube drawing methods available[2, 3] plug drawing is used for waveguide production as neither die sinking or mandrel drawing are suitable for the tightly toleranced internal rectangle dimensions required, e.g. ± 0·001 in. on 0·9 in. × 0·4 in. for WG16.

The principles of plug drawing are illustrated by the sketch of a typical draw bench (Fig. 1) and a section through the plug and die position (Fig. 2). Cylindrical tubes of larger cross-sectional area than the waveguide required are simultaneously drawn over a plug and through a die, the plug being positioned by a bar attached to the back of the bench such that the end of the plug is in the same vertical plane as the final face of the die, i.e. the plug is not allowed to pass through the die. Both the outside and inside tube dimensions, and the wall thickness, are reduced, a reduction of cross-sectional area of 30–40% per draw being possible. Rectangular waveguide is drawn from cylindrical tube in one operation, but single or double ridged waveguide is drawn to an intermediate cross-section before final precision drawing into the ridged form.

The drawing operation is very severe, stressing the metal above its elastic limit to achieve plastic flow through the die, and consequently it work-hardens the tube. Programming of cupping, re-drawing and annealing is therefore necessary in order to secure the required hardness in the waveguide tube, which is not usually subjected to annealing (except as indicated in Section 4).

The attenuation of electromagnetic energy propagated down a waveguide increases with increasing internal surface roughness[4] (see also Sect. 12). Mechanical polishing of the surface is not recommended because of the formation of a relatively high resistance amorphous layer at the polished surface.[5] Internal surface finish is therefore controlled by the finish of the plug and by the lubricants used in the drawing operation. The high standard of finish required in waveguides is obtained by using tungsten carbide plugs, which can be more highly polished than hardened tool steel and, being harder, also have a longer useful life. A typical improvement is from 20 micro-inches using hardened tool steel to 10 micro-inches using a tungsten carbide plug.

3. Electroforming of Waveguide Lengths and Components

Electroforming of waveguides was originally envisaged as being mainly applicable at millimetre wavelengths, where dimensional accuracies better than $\pm$ 0·001 in. and surface finish of the order of 5 micro-inches, are required. This process has also been found useful at lower frequencies, however, and is now extensively employed in manufacturing components up to and including size WG10 (2·840″ × 1·340″).

Standard lengths of electroformed Precision Waveguide are listed in Specification DEF–5351 for sizes WG22 (0·280″ × 0·140″) to WG32 (0·034″ × 0·017″), having nominal working frequencies of from 30 Gc/s to 300 Gc/s.

3.1. *Electroforming Processes and Materials*

The main considerations governing the choice of materials for electroforming waveguides are good conductivity, adequate strength to support its own weight, greatest corrosion resistance compatible with other requirements, and material should be non-magnetic. The best overall compromise is achieved by using copper, although an initial layer of silver may be used to improve conductivity. A hard deposit of nickel or chromium on an initial copper or silver layer has been advocated if severe wear is likely.[6] Aluminium electroforms have been produced where lightness is of paramount importance.

3.1.1. The cyanide copper process

This process has been described and recommended by Harvey[6] as meeting the requirements enumerated above, and having the advantage of producing a hard copper which facilitates the machining operations necessary for the attachment of coupling flanges. The process, originally developed in U.S.A. to provide a smoothly finished surface,[7] uses an electrolyte composed of cyanides of copper and of other elements, which is used with a periodically reversed plating current.[8] The object of the periodic reversal is to deplate unsound metal and nodules during the time that the electroform is anodic. Thus, although best results are obtained with anodic and cathodic currents nearly identical, the net product of time and current must be positive (component cathodic). Typical component cathodic and anodic times are respectively 20 to 100 and 10 to 40 seconds, depending on size and shape of components. A current density of 80 amperes per square foot, with 180° F bath temperature will give the optimum plating speed of 0·002 in. to 0·003 in. per hour.

In addition to the constant rotation of components which is normally advisable to ensure that all surfaces are equally exposed to the electrodes, whatever the electroforming electrolyte, this process also requires constant agitation of the bath, by bubbling air through it, and a continuously circulating filtration system.

A specific application of the periodic reversal cyanide process has been production of the standard lengths of precision waveguide listed in DEF–5351, covering WG22 (0·280″ × 0·140″) and smaller sizes.

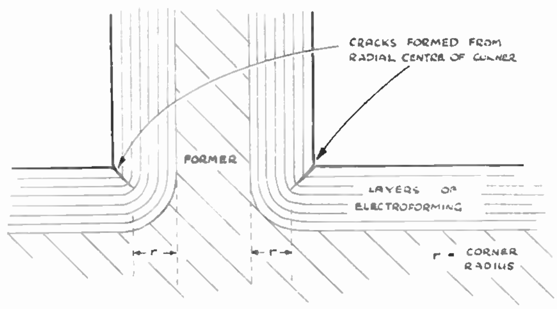

Fig. 3. Formation of cleavage plane at electroformed corners.

Inadequate deposits at internal corners and on re-entrant surfaces, due to the low electric field present, are a source of difficulty in electroforming. As shown in Fig. 3, a cleavage plane forms between the two surfaces from the depth of the corner arc radius.[29, 30] This may be overcome by increasing the arc radius beyond the plating thickness required, or by plating-in metal inserts at the corner.[6]

3.1.2. The acid copper process

As used for the electroforming of waveguides, this embodies several improvements on the standard acid copper (copper sulphate electrolyte) process used in other industries, and is the subject of a patent by Bailey.[46, 47] Most of Harvey's objections to acid copper have been overcome in this process, which includes the provision of suitably shaped copper bars, which are not electrically connected to the bath circuit, to improve throwing power into corners, etc. Regular inspection of the electroform and removal of irregular deposits is essential, however, as are the cleaning and degreasing operations carried out before returning the component to the bath, in order to prevent lamination of succeeding deposits.

Acid copper electroforming only requires the addition to the standard plating bath of equipment for rotating the components, and the bath operates at normal room temperature. The slower plating speed (0·001″ per hour) compared with the cyanide process may be economically overcome by the provision of additional or larger baths. The low temperature also allows the use of former materials which might distort at the cyanide bath temperature.

Machining of the soft copper deposited by this bath may be eliminated by plating-in such items as coupling flanges. Possible distortion of these softer (compared with cyanide copper) electroforms may be obviated by correct design of mechanical supports. An advantage of "acid" copper is that it has much lower internal stresses than the harder cyanide copper and is therefore more likely to maintain the precise shape of the former.

3.1.3. Electroforming of aluminium

Electroforming in aluminium is not at present in use as a commercial process, although possible methods have been investigated by Safranek *et al.*[31] in the U.S.A.; by Zeigler[32] in Germany; and by Balmer[32] in the U.K., who has produced waveguide components during his development work.

All of the proposed baths use volatile hydrocarbons, or their derivatives, and are operated in sealed vats in order to minimize the danger of fire and to prevent the absorption of atmospheric moisture. The Safranek and Balmer methods also require equipment for agitating and filtering the solution, periodic current reversal[32] or low density alternating current superimposed on the d.c. supply to the bath,[31] and the use of organic addition agents to ensure relative freedom from nodule formation. Even so the best deposits reported are 0·025 in. to 0·04 in. (hardness 40 to 140 DPH) by Safranek, and 0·1 in. (hardness 95 DPH) by Balmer.†

Drawbacks to the commercial use of solutions for forming aluminium may be summarized as: poor throw, slow deposition rate, fire risk (requiring the use of sealed vats), and reagent costs, which approach those for a silver plating bath. Any future use of these methods will obviously be restricted to applications where weight-saving is of paramount importance, and where fabrication from aluminium sheet or tube is impossible.

3.2. *Types of Formers*

By the nature of the process, both the dimensional accuracy and the internal surface finish of electroformed components are largely controlled by the same parameters of the formers on which they are deposited. These qualities are at their best in permanent metallic formers, with possible dimensional tolerances of ± 0·00002 in. and surface roughness better than 5 micro-inches. Microscopic measurements have shown improvements of 4 to 1 in surface finish when comparing electroformed and drawn copper waveguides[12] (see Sect. 12). Non-metallic disposable formers are used when the component shape would make the removal of a permanent former impossible.

† DPH = diamond pyramid hardness number (see B.S. 427: 1931).

3.2.1. Permanent formers

In order to avoid distortion during processing and stretching of the former during its withdrawal from the finished component, it is advisable to use materials of high tensile strength and yield point for the manufacture of metallic formers. Alloy steels suitable for hardening are commonly used. Stainless steels are convenient because of their resistance to cleaning and plating solutions and the relative ease of machining them, although eventually their inferior hardness produces scratching and pitting. Other possibilities are chromium-plated high tensile steels, molybdenum and titanium.

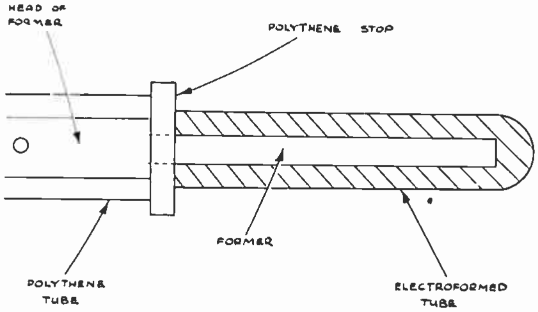

Fig. 4. Simple former and electroformed tube.

A typical waveguide length and its former are illustrated in Fig. 4. The polythene stop ensures that the face of the waveguide is square at the former head end, and the polythene tube extends from the stop to above the solution surface to prevent deposition on the former head. After assembly with the stop and polythene tube the former is subjected to chemical and electrolytic cleaning and given its first thin deposit in a weak solution "strike" bath. The former is then transferred to one of the baths previously described for deposition of at least 0·075 in. thickness, further deposition being governed by the strength requirements for the particular component. If an initial layer of silver is required it will be 0·075 in. nominal thickness.

With deposition completed the component is removed from the bath and washed before the former is extracted. Extraction is carried out in a machine designed to exert a vertical pull on the former with the component immersed in water or oil at about

200° F. The pull exerted restricts the maximum former length, due to the elastic limit of the former material, e.g. 10 in. for 0·280 in. × 0·140 in. cross-section.[6] If extraction is carried out in this way the former need not be tapered.

Although metallic formers are mainly used for straight waveguide sections (including smooth and stepped tapers, horn sections, etc.), some complex shapes, such as T-junctions and hybrids, may be deposited on formers made up of several interlocking parts. A disadvantage of this method is the "flash" thrown into the minute cracks between the parts. Jigs, which must be covered with a "stopping-off' compound, are also usually required to clamp or accurately align the interlocking parts.

Attachments to the formers and any associated jigs, in addition to the "stops" mentioned, may include parts to be "plated-in" (e.g. corner inserts or coupling flanges), copper bars to improve throwing power (as 3.1.2 above), and plastic sheets or cylinders to reduce throwing power in areas of high electric field intensity.

It is sometimes possible to retain plastic formers (as in 3.2.2 below) as permanent formers. Extraction is by refrigeration, differential contraction between former and component allowing easy removal of the former.

3.2.2. Disposable formers

Disposable formers may be made from any material which can be melted out of the electroform or disposed of by chemical solvent action without raising the component material to a temperature at which it will distort.

Metallic formers of a fusible alloy which melts out in boiling water, or aluminium with caustic soda as a solvent, may be used. Fusible alloys, however, tend to amalgamate with the component surface. As any metallic formers require individual machining these types are not generally used.

Non-metallic formers, produced in accurately machined moulds by a process similar to pressure die-casting, are convenient for large scale production. A methacrylate resin, Diakon, moulded at 30,000 lb/in^2, has been found suitable. This material has a small moulding shrinkage (1 %), low water absorption, and is easily removed by chloroform, but tends to distort from 120° F upwards. Dimensions of 0·280 in. by 0·140 in. may be held to 0·0005 in. using Diakon formers, but its use above millimetre wavelength sizes is not economic as the solvent action precludes re-use of the material. Polystyrene is also suitable, with trichlorethylene as a solvent. Removal time is improved by drilling out the former centre before suspending it in trichlorethylene vapour. Part permanent and part disposable polystyrene formers have also been used.

High melting point waxes (e.g. Seekay, melting at 100° F) are economically attractive as the wax may be re-used after melting it out of the component.

Since waxes and plastic materials are electrical insulators they must be given a conducting coating before plating can commence. This coating may be applied by immersion in a silvering solution, by twin-jet spraying with the two components of the silvering solution, by evaporation of a suitable metal under low pressure, or by spraying with a colloidal suspension of graphite. The latter is restricted to large waveguide sizes as the graphite is removed with the former material and surface finish is inferior to that produced by other methods.

The quality of surface finish obtained from disposable formers is governed by the finish of the mould surface and the homogeneity of the former material. Generally it is only slightly inferior to that obtained from permanent metallic formers.

3.2.3. Solid dielectric waveguide

If a plastic material, e.g. polystyrene rod, is used as the former for thin (0·007″–0·012″) plated waveguide, and retained as the waveguide dielectric, considerable saving in space and weight will result.[52] Differential expansion and contraction between the plating and dielectric may give rise to voids which will upset the electrical characteristics of the guide, although epoxy resin potting can overcome this. Flange attachment may be effected with an adhesive as soldering cannot be used. Projection of the dielectric beyond the flange face, mating with a tube having its dielectric recessed, may be used to aid axial alignment. Copper and silver waveguides of this type have been produced.

4. Fabrication of Components from Drawn Lengths of Waveguide

All waveguide runs constructed from drawn tube involve the attachment of coupling flanges to the ends of the tube sections, usually by brazing or soldering, and they also frequently include bends, twists or both in some tube sections. Soldering and brazing techniques are also used in the fabrication of components (e.g. directional couplers, tees, etc.) from drawn tube.

4.1. *Bending Techniques*

Methods of applying bending forces to the exterior of a piece of drawn waveguide tube will be detailed first, assuming that the interior of the tube is filled by an appropriate material during the operation. The various ways in which the internal dimensions of the bent tube may be maintained will then be considered.

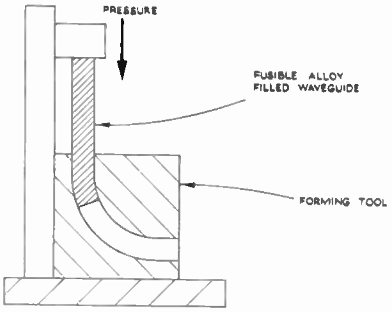

Fig. 5. Press tool bending method.

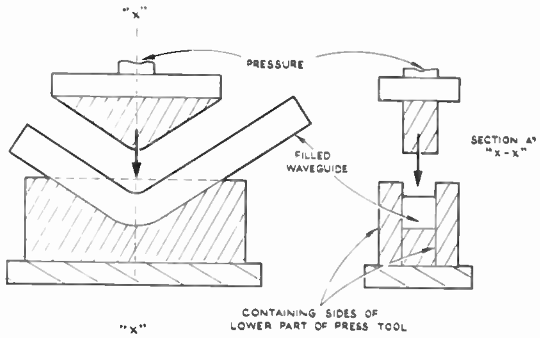

Fig. 7. Alternative press tool bending method.

4.1.1. The bending operation

Short lengths of tube may be bent in a power-operated press tool (Fig. 5), the guide length being forced down into the shaped tube formed by the tool.

The hand-operated bending bench illustrated at Fig. 6 is widely used. One end of the tube is anchored to the bench while a roller on the hand-operated lever forms the bend round the circular fulcrum. A recent American development[49] uses a similar principle in a hydraulically-operated bending machine operating on an automatic cycle.

In the third method, illustrated in Fig. 7, the wave-guide tube is deformed to its final shape by a press-tool of conventional design. This may be hand-operated with X-band waveguide, but requires power operation for S-band sizes. This type of tool has been adapted in America to produce tuned mitre bends.[49]

4.1.2. Maintenance of internal dimensions

The tube to be bent must be filled by some material in order to maintain even an approximation to the original cross-section round the bent section. Fusible alloys are commonly used in bending other types of tubes, and have also been widely used for waveguide bending by any of the three basic operations described above. A disadvantage of the fusible alloy filler is that it stretches round the outside of the bend, allowing the outside tube wall to be pulled inwards, thus reducing the distance between the walls at the mid-point of the bend. Reductions of up to 0·040 in. in the 0·400 in. dimension of WG16 tube may occur on a 90 deg E-plane bend (i.e. 10%). This reduction can be a serious embarrassment if the bend is used in a system carrying high peak powers.

A second disadvantage of fusible alloy filling is the tinning action that may result from direct contact between the alloy (usually of tin-lead-bismuth-cadmium) and the tube wall during the filling or emptying processes. Careful application of a thin homogeneous oil film to the waveguide internal surfaces should prevent tinning.

Over the past few years flexible steel laminations have been increasingly used as filling media during bending operations. These laminations are usually of $\frac{1}{32}$ in. or $\frac{1}{64}$ in. thickness and of width slightly less than the internal guide dimension of the plane of the bend. The laminations are packed into the guide as shown in Fig. 8. The final lamination to be inserted is of the elongated Y form shown in Fig. 9, and acts as a key, holding all of the laminations tightly in position. The laminations slide one against the other during bending, maintaining the cross-section around the bend and reducing the tendency of the outer wall of the bend to collapse inwards. This filling technique cannot be used with the first type of bending operation described in Section 4.1.1 above.

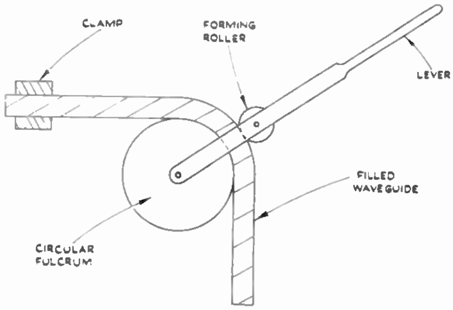

Fig. 6. Hand-operated bending bench.

Fig. 8. Lamination-filled waveguide prepared for a E-plane bend.

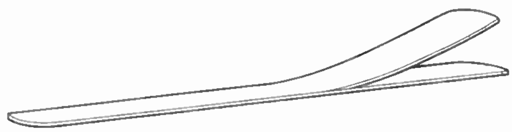

Fig. 9. Form of last lamination.

Improvement of the waveguide internal dimensions may be effected by retaining the tube in the press tool and passing a set of rollers through it, as shown in Fig. 10. A typical set is of twenty rollers, varying in steps of 0·001 in. from 0·380 in. × 0·880 in. to 0·400 in. × 0·900 in., for use with WG16.[48] As the rollers are pressed through the tube they exert a swageing action on the walls where the internal dimensions have been reduced. Double rollers, fed in after every fourth single one, are required to maintain the passage of the rollers normal to the tube walls.

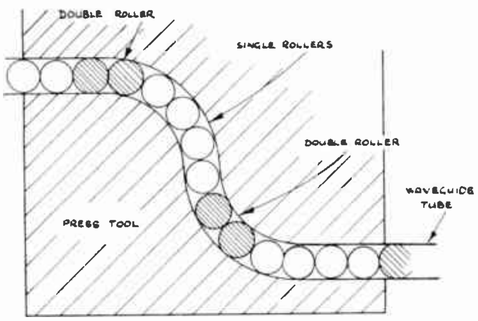

Fig. 10. Waveguide internal surface swageing rollers.

Maintenance of dimensions in the American hydraulic press method is by means of articulated rollers and mandrels. The American mitre-bend forming method uses a complex system of rigid mandrels, pressure-driven wedges and rotating mandrel inserts.[49]

Annealing (to counteract work-hardening) and cleaning processes will be required between the stages of some complex bending, and between bending and roller-swageing operations.

4.2. *Soldering and Brazing Techniques*

Successful soldering and flame brazing of waveguide components is probably more dependent on the individual operator's skill than is any other operation in their manufacture. Precautions which must be observed to ensure the production of acceptable components include cleaning and degreasing of materials to be used, effective wetting or tinning of surfaces to be joined, adequate heat control (to prevent burning of the metal), complete filling of the joint with solder or brazing metal (insufficient or excess metal may produce embarrassing discontinuities) and immediate washing after the operation to ensure complete removal of corrosive fluxes.

The precise nature of waveguide assembly usually requires the provision of accurate jigs or fixtures to maintain the relative positions of the tube and other components during the soldering or brazing operation. Exceptionally it may also require the supply of annealed sections of drawn waveguide of the precise length required. Self-aligning fits of the parts used, and fixtures which allow for expansion on heating of the parts will assist in minimizing distortion.[10]

A technique known as differential brazing can sometimes be used, and is illustrated in the assembly of an elbow at Fig. 11. Here sections 1 and 2 are first brazed together, using the highest melting-point brazing metal that is suitable, followed by lower melting-point metals, until the lowest melting-point metal suitable is used for brazing sections 4 and 5. This method ensures minimum distortion of a joint already made due to heat conducted to it from the next joint.

Dip brazing of waveguide components (usually aluminium or one of its alloys) is often used with either drawn tube or parts pressed from sheet material. This technique requires the positioning of fillets of brazing metal at the joints to be brazed, or the use of sheet materials with an integral coating of brazing alloy. As with flame brazing, the component parts must be accurately jigged with due allowance for expansion during the application of heat. The jigged assembly is preheated to just below the brazing metal melting point and then plunged into a bath of molten flux (usually salt). Close control of the bath temperature and the elimination of temperature gradients within the bath is essential as the difference between the melting points of the aluminium and the brazing metal is quite small. The surface finish of dip-brazed components can approach that of standard drawn waveguide.[52]

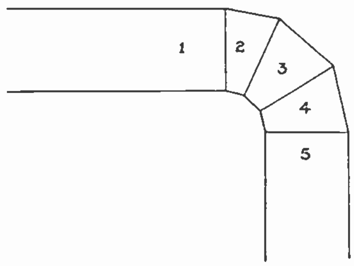

Fig. 11. Brazed waveguide corner.

5. Machining Operations used in Manufacturing Waveguide Components

Apart from the many standard machining operations (e.g. turning, boring, reaming, milling, etc.) used in obtaining attachment points, mating surfaces, etc., on waveguide components, several techniques have been developed or adapted to obtain the dimensional accuracy required for satisfactory operation of these components.

The methods described, other than spark erosion, are used when machining a component from solid block or sand cast material. Machining from solid has now largely superseded manufacture from rough castings, due to the lack of homogeneity in the latter. Unless stated otherwise, it may be assumed that the material used with the following techniques is aluminium, or one of its alloys.

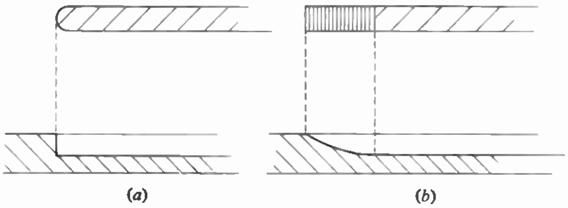

Fig. 12. (*a*) Finish of end mill cut.
(*b*) Finish of conventional slab milling cut.

5.1. *Milling Techniques*

Milling from solid block may be used to produce complete circuitry for microwave transmitting-receiving heads in one block, or for producing several interconnected hybrid rings or tees as one component. The final circuit is usually in the form of two mirror-image halves,[35] mating midway across the guide face, or the block may be milled to the full E or H plane depth, mating with a flat plate. In either case flatness of material is essential, and it must be stress-relieved before milling commences, to minimize bowing tendencies caused by the removal of metal from one side only.

End-milling is preferred to slab-milling, because of its greater flexibility and vertical face finish (Fig. 12). Prototype circuits are produced on manually-operated milling machines, but production runs are usually produced by copy-milling. The principle of one type of copy-mill is shown in Fig. 13, the milling cutter being directly coupled to the stylus tracing out the form of the master component. The master has previously been milled, under manual control, in a harder material than that used for the final component.

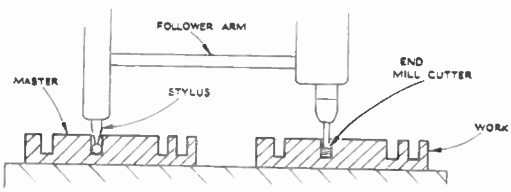

Fig. 13. Copy milling principle.

An alternative method uses a servo attachment to a standard end-milling machine. In this method a pressure-sensitive stylus is guided round the master by hand and the table of the milling machine moves to oppose the direction of pressure on the stylus. The dimensional accuracy of these methods is controlled by initial setting-up accuracy, table or linkage backlash, rigidity of cutter mounting, and matching of stylus and cutter sizes, which should be within 0·001 in. for accuracy of the same order.

Digital computer controlled end-milling, using a three co-ordinate system may also be employed.[11, 17] Here positioning of the component is automatically checked, using optical gratings, to an accuracy of 0·0001 in., although accuracy of the finished component is determined mainly by cutter wear and whip in the cutter mounting.

5.2. *Routing*

Routing has been developed, from the well-known method of wood machining, for use with aluminium alloys. The cutter is similar in form to that used in copy-milling, the main difference between the two techniques being the high speed (18,000 to 24,000 rev/min) of the routing cutter.

The principle is shown in Fig. 14. The metal block is clamped above the template in a jig which may be manoeuvred on the machine table. The stylus projects through the table to engage in the template grooves. Here also accurate matching of stylus and cutter sizes is essential.

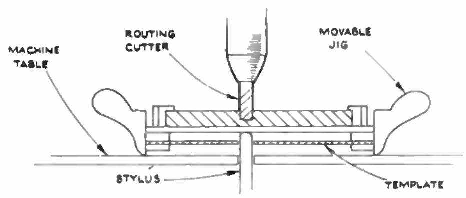

Fig. 14. Principle of routing.

Routing is possibly a faster production method than copy milling, but likely to be slightly less accurate and with inferior surface finish, due to the manual control of the template positioning.

5.3. *Hobbing*

Hobbing is a deformation process in which a male counterpart of the component to be produced is pressed into a cylindrical blank (Fig. 15). Its application to waveguide components is mainly in the production of smooth and stepped tapers, which are very difficult to achieve by other machining methods.

The hob is made of hardened steel and is an exact negative of the cavity required. No taper is necessary if this is not an electrical requirement. Considerable care must be exercised in the choice of hob material, according to whether it is to be used for cold hobbing of aluminium, or hot hobbing of copper or brass.

During the hobbing operation flow of metal in the blank is restrained from any lateral movement by a

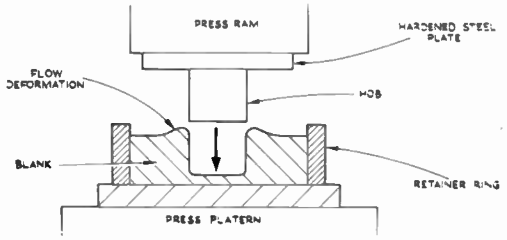

Fig. 15. Hobbing operation.

retainer ring placed around it. Thus deformation appears only on the upper surface. Since the tool is not allowed to break through the lower surface both ends of the component require subsequent machining.

Tool extraction may be by reversing the power press used to insert it, if this is possible, or by transferring the component to a clamping jig in a reverse fly-press. Hot hobbed components are quenched before tool extraction, in order to shrink them to the precise dimensions of the tool. The internal surface is polished by tool extraction and comparable with that of drawn waveguide. Dimensional accuracy is of the order of ± 0·001 in.

5.4. *Broaching*

Broaching is the surfacing of work by means of a series of small cutting edges on tools which are forced through or past the work. It is commonly used to produce rectangular or irregularly shaped holes. This is an ideal method for making the finishing cut of a waveguide aperture passing through the thickness of a milled block, e.g. the hybrid tee H-plane arm of Fig. 16, or of the rectangular hole in waveguide coupling flanges. Surface finish and dimensional accuracy depend on the number, size and sharpness of the teeth in the tool, but may be of the same order as for drawn tube when fine toothed tools are used.

5.5. *Spark Erosion*

Spark erosion machining is a technique only recently adopted in this country,[15, 45, 59] although it has been widely used in the U.S.S.R. for several years.[20]

The technique depends on the erosive action of a rapid succession of spark discharges between two electrodes, the tool (a male counterpart of the hole required) and the work piece. The basic electrical circuit is simple, as shown in Fig. 17. Impulses to the tool electrode are fed from the capacitor (usually between 20 and 500 μF), which is charged through a current limiting resistor from a d.c. source of 100 to 250 volts; charging currents are normally less than 5 amps.

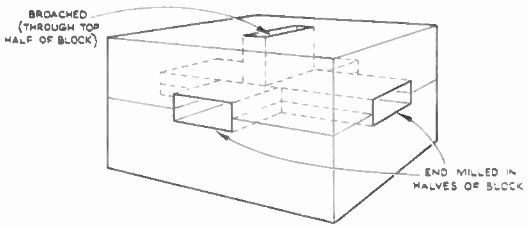

Fig. 16. Application of broaching.

Tool and work piece are immersed in a non-conducting liquid (e.g. transformer oil) which acts as a cooling agent, and also intensifies the erosive effect, due to its incompressibility. The spark discharge atomizes the surface of the work piece, giving a finish consisting of a series of overlapping lunes, of size and depth proportional to the discharge energy. Surface finish at economic erosion speeds is not usually better than 100 micro-inches. Dimensional accuracy of ± 0·001 in. is possible at 0·4 in. hole diameter.[20]

Brass tools of 60% copper content appear to be the best compromise between working efficiency and erosion resistance. Tool wear is of the order of 1 to 6 by weight, compared with the material eroded from the work piece.

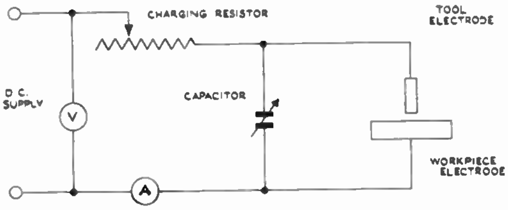

Fig. 17. Basic spark erosion circuit.

The main applications of spark erosion in waveguide fabrication are slotting of couplers and radiating elements, when it is impossible to use conventional machining methods. Surface finish is not of outstanding importance in these applications.

6. Assembly from Pressings

Assembly of waveguide components from mass-produced pressings is economically attractive where large quantities are involved, although acceptable tool wear may be less than that normally allowed in press-shop production.

6.1. *Seamed Tubes*

Fabrication of straight lengths of waveguide tube from two identical top-hat sections is accepted in DEF–5351 as a normal production method for size WG6 (6·500″ × 3·250″) and larger.[1] The join between the two sections, midway across the broad face, is normally welded. This technique has recently been adapted for use at smaller waveguide sizes, using two mirror-image sections to fabricate bends, and using spot welding, soldering, dip-brazing, riveting or folding as alternative joining methods.[52]

6.2. *Laminations*

A method has been developed in the U.S.A. which builds up complex twisted waveguide sections from 0·005 in. thick laminations.[52, 53] Individual laminations are rectangular, with the appropriate rectangle size punched in the centre and a hole in each corner. The number of laminations required for the tube length are stacked together with four wires threaded through the corner holes and squeezed together between special flanges at each end. This assembly is placed in a jig which aligns the flanges as required, imparting the twist. To prevent further sliding of adjacent laminations the stack is soldered over the outer surface, producing a solid unit. Applications of this technique are limited to complex twists which it would otherwise be impossible to manufacture.

6.3. *Twisted Tag Technique*

This assembly method, sometimes referred to as the "German toy technique", is covered by a G.E.C. patent[39] and has been successfully used for quantity production of complex assemblies. The principle is illustrated in Figs. 18 to 20, and bears some similarity

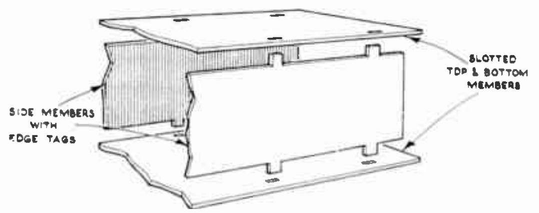

Fig. 18. Partial components for simple "twisted tag" waveguide.

to the slot and tag assembly method used in toy manufacture. The four components shown in Fig. 18 are produced by standard press-tool methods from aluminium alloy sheet coated with brazing metal.

The four components are shown assembled in Fig. 19, with the protruding tags twisted at 45 deg, giving a relatively rigid, self-jigged assembly. An alternative method of deforming the tags, by indenting the tag between two dies, is shown at the right of Fig. 20. Coupling flanges and other components may also be included in the assembly. The final stages of assembly are dip-brazing (see Section 4.2), followed by removal of the tag ends, by twisting or machining.

Using this assembly method for large quantities it is economic to bypass precise mechanical inspection (except for interchangeability features) and accept or reject purely on electrical performance.

7. Metal Spray Technique

The technique of building-up waveguide components by spraying metal on a retractable former was developed by Ives at the Admiralty Signal and Radar Establishment.[9, 14]

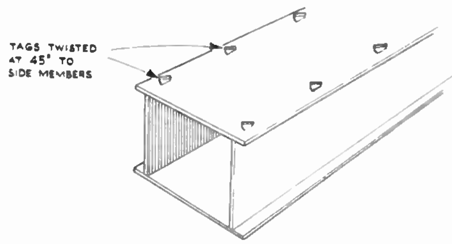

Fig. 19. Simple "twisted tag" waveguide assembly.

As for electro-deposition, the former is an exact negative of the part to be produced, and must be thoroughly degreased prior to use. The former is first sprayed with a soluble stoving lacquer, or with a crystic water-soluble lacquer. The lacquer coating, of approximately 0·0003 in. assists the bonding of the metal spray and is usually coloured, in order to aid the operator in assessing the homogeneity of the initial metallic coating. The former is then sprayed with the metal, using a wire-fed gun with 1–2 mm diameter wire. On completion of the spraying the component may be machined to size externally, either before or after extraction of the former. Extraction is usually by means of a press (as for hobbing tool extraction), and the lacquer is then removed by the appropriate solvent.

Formers may be made of any suitable metal, e.g. brass, steel, stainless steel, and may be of multiple form for complex components, as in electro-deposition. Experimental work has been carried out using plastic and rubber formers. The impact of the sprayed metal particles raises the temperature of the component, but formers may be water-cooled to prevent melting of the lighter metals used, and in order to maintain production speed.

The structure of the sprayed metal is similar to that of a casting, but more porous, with a tensile strength of only 25% of that for equivalent wrought material. Vacuum impregnation with a suitable resin can improve this figure to 60%. Metals which have been used successfully are zinc, brass, copper, steels, tin, silver-cadmium alloy, silver-tin alloy, and nickel alloys. An initial layer of 0·01 in. to 0·02 in. of the structurally weaker metals, e.g. zinc or tin, may be

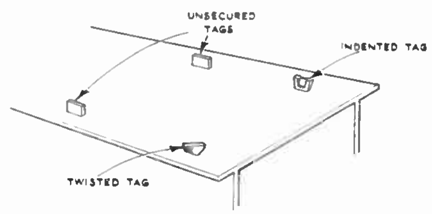

Fig. 20. Securing method for "twisted tag" technique.

sprayed on followed by brass, steel, etc., to provide structural strength.

Dimensional tolerances are comparable with those of electroformed components,[14, 52] and surface finish can approach that of drawn waveguide of the same material.[12, 13, 14] Ives claims a saving of up to 90% of time and labour compared with fabrication or electroforming methods, which makes this an attractive technique for producing experimental components, though its structural weakness will restrict large scale production use.

8. Casting Techniques

Sand casting and shell moulding (resin-bonded sand moulds) are almost invariably unacceptable for manufacturing waveguide components, due to the poor initial surface finish, and the underlying porosity which appears when machining operations are carried out on the castings. Such machining would, of course, be inevitable on sand castings, because of the large dimensional tolerances required by that technique. Other casting methods, which produce more homogeneous components with acceptable tolerances and surface finish, have been adapted to waveguide component production. Aluminium alloys are commonly used in the methods described, although magnesium or copper-based alloys may also be used.

8.1. *Die Casting*

The cold chamber pressure die-casting technique[36] is used to produce waveguide components in aluminium alloys. In this process the molten metal is ladled into the injection cylinder by hand and the rest of the process, i.e. application of pressure to the injection plunger and ejection of the casting, is automatic. For this process the dies can only be designed to produce separate halves of the waveguide section, so that two sets of dies are required for each complete component. As these dies are the product of precision tool-making, die casting is only economically attractive for very large quantities. A 1 deg draft on the split side is normally required to assist extraction, but this has no serious effects on the electrical parameters of the waveguide.[55] Dimensional tolerances are normally ± 0·005 in. The casting surface is microscopically rough and porous, a typical mean c.l.a. (centre-line-average) roughness figure being 25 micro-inches,[13] which is sufficiently good for X-band, and larger, guide sizes.

8.2. *Investment Casting*

The first step in the investment, or "lost wax", casting process is the manufacture of a split mould which is used to prepare a wax replica of the component required. Heated wax is injected into this mould while it is held in a water-cooled vice. The wax pattern is removed from the mould, placed in a moulding frame and covered with a plaster slurry. When the plaster coating has set it is heated for several hours, to dry the plaster thoroughly and melt out the wax. The plaster mould is then used to produce the casting by gravity, vacuum or low pressure (3–30 lb/in^2) methods. When the casting cools the mould is broken away and the component fettled, cleaned, etc.

Dimensional tolerances and surface finish are similar to those for die-casting,[21, 52] with the advantages that no tapers are required, and that more complex components may be manufactured than with metal dies.

8.3. *Frozen Mercury Investment Casting*

The frozen mercury investment method[16, 54] is similar to that described above, with frozen mercury replacing wax as the pattern material.

The metallic die is filled with liquid mercury and frozen at about −65° C. The mercury pattern is then extracted and invested with a zircon-based ceramic shell up to a thickness of approximately ¼ in. The finished mould, after high temperature firing, is permeable and strong enough to withstand various casting methods, such as centrifugal, vibration or suction casting. The die metal must withstand amalgamation or attack by the mercury, suitable materials being steel or hard anodized aluminium. Two separately produced mercury patterns will readily coalesce or weld under light pressure, and this unique property may be used, with appropriate accurate jigging of the welding operation, to produce patterns of a complexity impossible to achieve in other casting methods.

The absolute limit of dimensional accuracy is ± 0·001 in., with surface finishes of 30–40 micro-inches in aluminium alloys and 50–60 micro-inches in copper alloys. Normal internal waveguide tolerances are ± 0·002 in., no draft allowance being necessary, and wall thicknesses may be maintained down to 0·08 in.[50, 52, 54]

8.4. *Plaster or Ceramic Mould and Core Methods*

Several other methods of investing plaster or ceramic moulds have been developed using metallic patterns, free-machining brass being a frequent choice for pattern material. Of necessity, split moulds are produced by these methods, and cores must be used for the inside of the guide. Accurate and convenient location of the parting face is necessary during investment of the pattern.

A gypsum-based slurry is normally used to produce disposable plaster mould halves, but a variation of this material has resulted in "semi-permanent" moulds, which, it is claimed, remain usable for quantities of up to 500 castings.[18] All cores are inevitably disposable, and may be made from the normal slurry, or from a recently developed variation which, although it has adequate strength for casting purposes, disintegrates into a soft mush when wetted, and is easily flushed away. This avoids the possibility of damaging the internal surface which can occur when using normal methods of core disposal.

Dimensional tolerances may be held to ± 0·003 in., with internal surface finish of 20–30 micro-inches.[12, 13, 19]

9. Flexible Waveguides

Flexible waveguides were developed in order to maintain a matched and reasonably low loss connection between two waveguides having some motion relative to each other. The types of motion and their frequency vary over wide ranges. Small displacements between solidly and flexibly mounted equipments may vibrate at frequencies up to several kilocycles per second. Complex bending and twisting motions between airborne radar transmitter-receivers and scanning units using pitch and roll compensation may occur at between 5 and 50 cycles per minute. The availability of flexible waveguides has encouraged their use in purely static roles also, where the displacement between two guides is large and/or unpredictable.

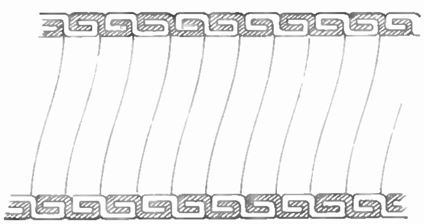

Fig. 21. Part section of flexible waveguide showing interlocking principle.

All convoluted (i.e. interlocking and formed bellows) types of flexible waveguide give rise to many small reflections between the convolutions, but most of these are cancelled by equal reflections, 180 deg out of phase, from further along the guide. Thus, neither attenuation nor v.s.w.r. are as bad as might be feared from the irregular appearance of the inside surface, typical figures being 0·15 dB per foot at 0·95 v.s.w.r., although precise performance varies with the type of convolution and design bandwidth. Power-handling capacity is usually somewhat below that for the equivalent drawn waveguide size.

All flexible waveguides are supplied with the required coupling flanges hard- or soft-soldered to the ends; the flanges are usually of slightly larger aperture than those used with drawn waveguide, to assist in

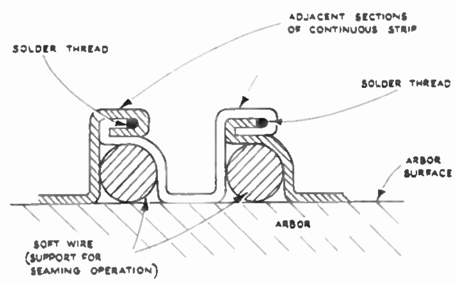

Fig. 22. Principle of construction of soldered interlocking tube shown on winding machine arbor.

matching the convoluted and plain guides to each other.

Convoluted waveguides are normally enveloped in a strengthening, and possibly pressure-tight, moulded rubber jacket, which may be moulded straight, or preformed in a shape required for a specific application.

9.1. *Interlocking Type*

A section through an early example of this type of flexible waveguide is shown in Fig. 21. This uses the principle employed in the manufacture of standard circular section metallic hoses, the tube being formed by interlocking the adjacent edges of a continuous metal strip, as it is wound on a mandrel or arbor, of rectangular section for flexible waveguides.

In a later variant of this type the interlocking edges are continuously soldered, to improve conductivity and to prevent ingress of rubber to the inner surface.[23] Figure 22 shows a section through two convolutions of one side of the guide on its arbor. The soft wire, usually aluminium, is wound on the arbor at the same time as the metal strip and solder thread; it acts as a support or anvil during seaming, and is removed when seaming is completed. Shaped rollers perform the seaming operation, accurately following the sides of the rotating rectangle, and a gas jet playing on the interlocked tube performs the soldering operation as the guide proceeds along the arbor. This type of waveguide will flex in either plane, but cannot be subjected to twisting motions. A section through a single convolution of the modified, twistable, type is shown in

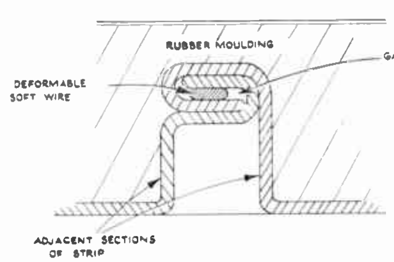

Fig. 23. Section through single convolution of twistable interlocked guide.

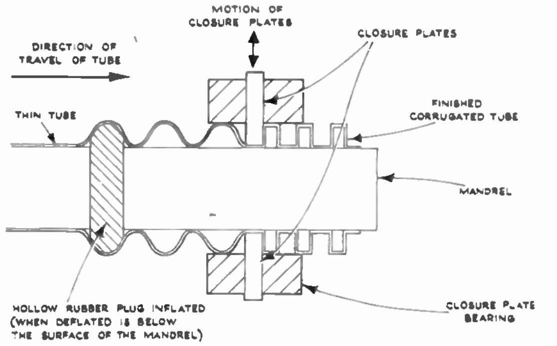

Fig. 24. Method of forming seamless bellows type flexible waveguide.

Fig. 23. A deformable soft metal wire (e.g. aluminium) is substituted for the solder thread and maintains good conductivity between the interlocked sections, while restricting the ingress of rubber to as far as gap A.[24] Typical attenuation and v.s.w.r. figures are as stated above, for either modern type, with a power-handling capacity of better than 200 kW at X-band.[51]

9.2. *Formed Bellows Types*

Forming of a convoluted waveguide from thin rectangular tube is shown in Fig. 24. The hollow rubber plug is inflated at high pressure to deform the metal in a roughly semi-circular bulge, the closure plates are then brought in towards the axis of the tube, thus closing up the bulges to form rectangular-shaped corrugations, as the tube proceeds along the mandrel in corrugation-pitch steps.[22, 26]

This type of flexible guide may be used for sharper bends than are possible with other convoluted types, but having no axial freedom it will only survive minor twists undamaged. It is sometimes used without any rubber covering. Typical characteristics for X-band are 0·07 dB/ft attenuation at a v.s.w.r. of 0·93.

Another variant of this general type is assembled from two identical shallow U-shaped corrugated lengths.[25] The corrugations are shaped at the edges of the "U" such that if one length is inverted and placed on the other the edges mate and may be soldered together, as shown in Figs. 25 and 26. Manufacture is simpler than for other types, requiring a press tool to produce the "U" forms and an assembly jig to locate the two halves accurately for soldering. The preferred material is beryllium copper.

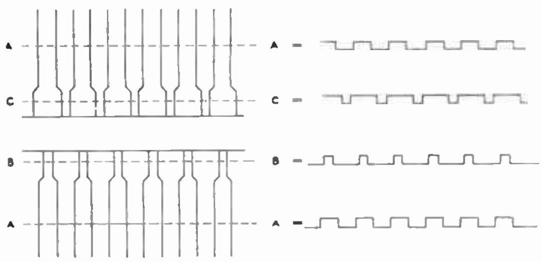

Fig. 25. Form of opposing edges of "U" sections.

Mechanical properties are similar to the seamless type, but with less flexibility in the H-plane. For X-band typical attenuation is less than 0·15 dB/ft at better than 0·9 v.s.w.r. over a bandwidth of 4·2 Gc/s, and power-handling capacity of 250 kW.

9.3. *Electroformed Types*

Lines and Balmer have patented an electro-deposition method of producing a flexible waveguide similar to the seamless type described above, but with semi-circular convolutions which increase the efficiency of deposition. Polystyrene or other suitable plastic formers are used and dissolved out by the appropriate solvent (see Section 3). Electrical performance figures are not available for this type.[27]

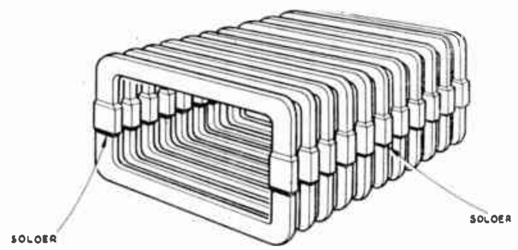

Fig. 26. Assembly method for soldered bellows type of flexible waveguide.

Anderson has produced a flat-surfaced flexible similar to the plated waveguide described in Section 3.2.3, depositing aluminium on a p.t.f.e. dielectric.[28] Rectangle size was decreased from 0·9 in. × 0·4 in. to 0·625 in. × 0·278 in. for X-band, but attenuation was increased five-fold. Difficulties were also encountered from differential expansion, as in 3.2.3.

9.4. *Vertebrae Type*

As illustrated in Fig. 27, the vertebrae type of flexible waveguide consists of a number of choke-grooved sections, similar to waveguide choke flanges mounted in a vulcanized rubber jacket.[22, 51] Simply stated, the principle of this type of waveguide is that the short-circuit at the bottom of the choke ditch $\frac{1}{4}\lambda_g$ deep, situated $\frac{1}{4}\lambda_g$ from the guide surface (at the centre of the E-plane) transforms to a short-circuit between the adjacent sections at the guide surface. These dimensions are somewhat modified in practice to

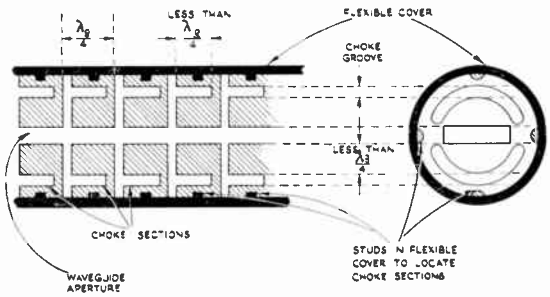

Fig. 27. Construction of vertebrae type flexible waveguide.

avoid unwanted resonances with axial displacement of the guide. The guide sections are usually machined from aluminium alloy.

Odd numbers of choke sections ensure cancellation of mismatches from individual junctions.

Although the vertebrae type has more degrees of flexibility than any other type, it weighs several times more than the same length of any other type. Typical electrical performance for an X-band guide $5\frac{1}{4}$ in. long (nine sections) is 0·2 dB attenuation at 0·93 v.s.w.r., with power-handling capacity of 250 kW.

PART 2. INSPECTION METHODS

10. Introduction

Three principal methods of inspecting microwave components have been defined by Byrne[33] as follows:

(i) Explicit mechanical inspection, i.e. direct inspection of the part by measurement of size, shape and position.

(ii) Implicit mechanical inspection, i.e. inspection of the former, mandrel or tool from which the part is produced.

(iii) Electrical inspection, i.e. the measurement of one or more specified electrical characteristics of the component.

Techniques used in methods (i) and (ii) are outlined, together with some consideration of interchangeability requirements for waveguide couplings and a short discussion of the inspector's function, responsibilities and difficulties.

11. Inspection for Dimensional Accuracy

It is self-evident that internal dimensions of waveguide components are generally required to be produced with smaller dimensional tolerances than those given to external features. The problems associated with measuring internal dimensions are usually greater than are met when measurements are made externally. These problems are aggravated because of inaccessibility in many waveguide components, e.g. tees, hybrid rings and complex bend and twist combinations, and may often be solved only by the use of implicit inspection methods.

11.1. *Implicit Inspection*

Implicit inspection may be carried out by measurement of the former, mandrel, plug, die or mould used in such processes as electro-deposition, tube drawing, die casting or metal spraying. Periodic checks of these tools, together with a knowledge of such features as shrinkage, will confirm the continued production of satisfactory components and also assist in forecasting the end of a tool's useful life. Critical cases of this type are metallic mandrels for electroformed waveguide of WG 22 size (0·280″ × 0·140″) and smaller. For example, WG26 dimensions are 0·1220 in. ± 0·0003 in. by 0·0610 in. ± 0·0001 in., and as several parts in 10^5 are stripped off the mandrel surface each time it is withdrawn its dimensions are soon reduced to the minimum acceptable.

In those cases where expendable formers, patterns or cores are used implicit inspection would be directed to measurement of mould or die dimensions, supported by periodic checks on sample formers, etc.

Examples of implicit inspection referred to this production stage are moulds for producing plastic formers for electro-deposition, core moulds, and moulds for producing wax or frozen mercury patterns. Precise measurement of bending tools, swageing rollers and of other tools and jigs used in fabrication from tube, strip or sheet material, carried out periodically, will assist in maintaining the output of satisfactory components.

When internal features such as matching irises or posts are either cast-in or plated-in they may become inaccessible for precise measurement. Implicit inspection, by examining the position of the part in the die, mandrel or mould before commencing the process, may be the only method of verifying that it is correctly positioned, apart from electrical testing.

Ideally all implicit inspection should be supplemented by precise measurement of sectioned samples of the final components, the frequency of sampling being governed by consideration of the component's complexity and the quantity to be produced.

11.2. *Explicit Inspection*

As a guide to the problems arising from the explicit inspection of waveguide components, and to the methods used, the specified requirements for waveguide tubing will be considered in some detail. The requirements to be satisfied are given in Specification DEF–5351.[1] Those covering the supply of a commonly used waveguide size, WG16, are listed below to indicate typical tolerances:

Nominal stock length	120 in. ± 2 in.
Inside rectangle	0·900 in. ± 0·001 in. × 0·400 in. ± 0·001 in.
Outside rectangle	1·000 in. ± 0·001 in. × 0·500 in. ± 0·001 in.
Mean wall thickness	0·050 in.
Maximum displacement of rectangles	0·0025 in.
Inside corner radius	0·030 in. maximum.
Outside corner radius	0·025 in.–0·035 in.

All the above dimensions must be checked on every tube, and the following additional measurements are made on a batch sampling basis:

Bow, over two points 2 ft apart	
Edgewise	0·010 in. maximum.
Flatwise	0·020 in. maximum.
Twist	1 deg per ft maximum and 3 deg maximum over the stock length.
Internal surface	13–25μin. c.l.a. (varies with material).

The external rectangle dimensions may be easily verified using GO/NO-GO gap gauges, or by direct measurement using a micrometer or vernier. Similarly, GO/NO-GO gauges may be provided to prove that the external corner radius is within limits.

Measurement of the internal rectangle to a tolerance of ± 0·001 in. over a 10 ft length, however, is a major problem. It is the usual practice to check both ends of the tube with GO/NO-GO plug gauges, or with precision slip gauges. Either method will provide only a limited penetration of the tube, a few inches at most. Dial micrometers with extended arms give some further penetration, but cannot approach the 5 ft penetration required for the tube quoted. Pneumatic plug gauges would appear to be the ideal answer to this problem. The principle of this type of gauge is illustrated in Fig. 28. As the distances between the two opposite tube walls and the jet orifices in the

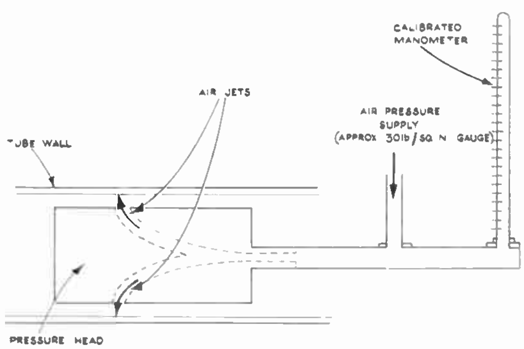

Fig. 28. Principle of pneumatic gauge.

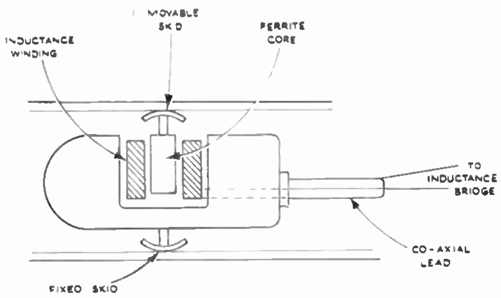

Fig. 29. Principle of ferrite cored inductance head.

pressure head vary, so the air pressure supplied varies. This pressure variation is measured on a manometer which may be adjusted in sensitivity to give ¼ in. movement in the manometer for 0·0001 in. variation in the tube dimension. The two air jets are equal and opposed, thus centralizing the pressure head in the tube. Two pressure heads are required for each tube size, one for each plane of measurement. At present use of this method is restricted to short lengths of tube which are required with smaller tolerances than those specified in DEF–5351. Its use will probably be extended to cover standard sizes and lengths, although the greater difficulty of designing suitable heads may exclude its use for very small sizes.

A recently developed instrument,[34] which is not available commercially, may also assist in overcoming the internal rectangle measurement problem. The principle of operation of the measuring head may be studied by reference to Fig. 29. This head, or probe, contains a ferrite-cored inductor, which forms the unknown arm of a bridge circuit. The bridge is completed via a flexible co-axial cable, in an associated unit, which also contains the power supply and oscillator. Variations in the tube dimension move the shoe attached to the core, providing an unbalance current from the bridge, which may be calibrated in terms of shoe movement. Accuracy is maintained by reference to a precision ground U-shaped standard. An accuracy better than 0·001 in. is claimed over a range of ± 0·014 in. The instrument was developed to provide accurate measurement of internal tube dimensions round bends, with particular reference to distortion of E-plane bends intended for high power use. The present probes will negotiate 2 in. inside radius H-plane bends, and 10 in. inside radius E-plane bends in WG15 (1·122″ × 0·497″). As for pneumatic gauge heads, two probes are required for each tube size.

Wall thickness and rectangle displacement (derived from wall thickness and rectangle dimensions) can only be accurately measured at tube ends, or where a tube is sectioned for any sampling checks.

The bow and twist limits refer to the tube inside rectangle, but it is difficult to make such measurements internally and they are normally carried out on external surfaces with very little additional error. The bow of drawn tube is measured by placing the tube on a precise flat surface, with the face to be measured in a vertical plane. A flat surface is brought in contact with the two extremities of the concave side, and precision slips inserted between the flat and the tube surface to measure the deflection.

The basic method of estimating twist is illustrated in Fig. 30. The suspended tube is not acted on by any external stresses which might oppose the twist. Monochromatic light is used to throw a shadow from the vertical plane before the tube is clamped to it. When the tube is in position the angle between the shadow from its lower end and the position of the original shadow is the angle of twist.

An alternative method is to measure the transverse slope of the tube face, when placed on a flat surface, with a clinometer. The tube and clinometer weight tend to counteract the twist, but allowance can be made for this (approximately 10%). The suspension method gives only the total twist over the tube length (accuracy not better than 5 min), but clinometer measurements may be made at any interval along the length, with an accuracy of 1 min.

A third method, which has been used with electroformed lengths, is shown in Fig. 31. This requires the manufacture of precision plugs to fit the guide ends. As shown, measurement of the linear deflection between appropriate plug face corners gives the tangent of the twist angle.

Another method, which has been used for estimating both twist and bow in long guide lengths, involves the optical measurement of linear and angular displacements between a graticule at one end of the tube and a second graticule which is drawn along its bore.

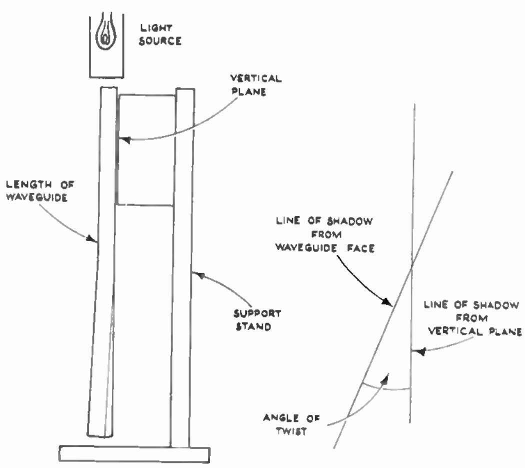

Fig. 30. Suspension method of measuring twist.

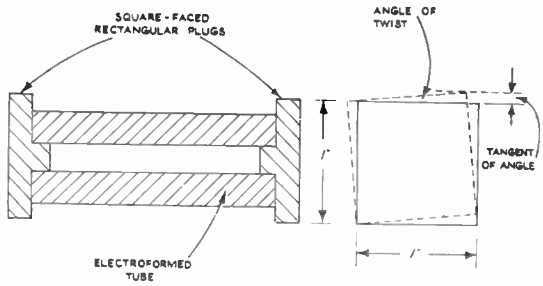

Fig. 31. Twist measurement on electroformed guide.

12. The Assessment of Surface Finish

Surface roughness is specified in DEF–5351 in terms of δ the depth below the surface at which the r.f. current has fallen to 1/e of its surface, maximum, value. The maximum permissible surface roughness is $\frac{1}{2}\delta$, c.l.a. Skin depth varies with frequency, as $\delta = \sqrt{\frac{2}{\omega\mu\sigma}}$; thus for copper, it decreases from 50 micro-inches at 3 Gc/s to 12 micro-inches at 48 Gc/s, giving surface roughness maxima of 25 micro-inches for WG10 and 6 micro-inches for WG24. Morgan[4] has shown that r.m.s. surface roughness of depth δ increases the guide attenuation by 60% on the theoretical figure, while roughness of $\frac{1}{2}\delta$ gives a 20% increase. Thus the specified roughness ensures that attenuation from this cause is less than a 20% increase. The reason for this increase is illustrated in Fig. 32, where measurement of the actual length of the surface (which is the path followed by the current) will show that it is approximately $1{\cdot}4x$, where x is the nominal length of the waveguide section.

Ideally the actual surface length should be measured and compared with the nominal length in order to assess the increase in attenuation from this cause. Such measurements have been made by Benson[12] using a technique which involves plating the surface with a contrasting coloured metal, sectioning the surface, polishing the section and measuring the length of the interface between the metals, using a microscope or projector. This is not practical for production inspection.

The first attempts at defining the surface finish required on waveguide interiors used such terms as "smooth" or "mirror" finish, etc. Assessment was made from visual and tactile information, and was subjective, based on the individual inspector's past experience.

A second visual and tactile method, using a surface finish comparator was developed by Harvey.[5] The comparator reproduces twelve standards of finish considered to be useful for microwave component surface assessment: lap 2, grind 4, 8, 16, 32 and 63, turn 8, 16, 32 and 63, mill 32 and 63, in micro-inches, c.l.a. Comparisons made using this guide are still largely subjective, however, and Harvey estimates overall accuracy of assessment at between +50% and −25%, though it is doubtful whether this can be maintained without long experience in use of the comparator, especially when assessments are required over a wide range of metals.

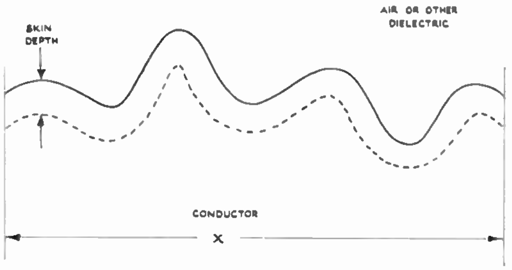

Fig. 32. Increase of current path length with surface roughness.

A stylus type instrument[37] may be used as a true comparator, calibrated against known roughness standards. Reference to Fig. 33 illustrates the principle of this instrument. A stylus of tip radius approximately 0·0001 in. follows the form of the surface irregularities, moving perpendicularly about a datum provided by the skid support. Probe and skid are driven over the surface for a predetermined sampling distance (usually 0·03 in.) at a fixed rate, and stylus movements are traced on a synchronously driven graph, or may be electrically integrated for meter display. The centre-line-average height (c.l.a.) is calculated from the graph. C.l.a. is defined[38] as: "The average value of the departure of the profile from its centre line, whether above or below it, throughout the prescribed sampling length". Manually propelled meter indicating instruments are also available, but are slightly less accurate.

Optical interference techniques, using monochromatic light and observing the interference fringes under a microscope, may also be used. For example, green light interference fringes are approximately 0·00001 in. apart, and irregularities in the fringes, indicating surface scratches, etc., are estimated in relation to this distance.

Because of the small surface area used in the measurement, it is only possible to use stylus type instruments and optical interference techniques for batch sampling, particularly if the inaccessibility of the surface requires sectioning of the component before measurement is possible.

The specification of surface finish for implementation as a 100% acceptance criterion is a difficult problem. Possibly the best answer for components in quantity production is to provide a "worst acceptable" standard component, for visual and tactile comparison, selected with the aid of electrical test results.

13. Waveguide Couplings—Interchangeability Considerations

As virtually all waveguide sections or components are interconnected by coupling flanges, it is apparent that these flanges are produced in larger quantities than any other microwave component. Interchangeability between all coupling flanges of a particular type and size is therefore of prime importance.

This interchangeability is necessary so that it may be assumed that, for a particular coupling flange type and size:

(i) Any flange may be fitted to any waveguide tube, which is within its specified outside rectangle tolerances, without encountering mechanical interference.

(ii) When coupling together two waveguide components the mating flanges should be compatible, i.e. bolt holes, locating keys and keyways must be correctly sized and aligned, and the threads of screwed ring couplings must be of correct size and threadform.

(iii) The mechanical interchangeability outlined above should ensure that electrical interchangeability is also achieved, i.e. that the electrical discontinuity at the junction of any two flanges, even if the two flanges used are made to the opposite extremes of all dimensional tolerances involved, is within the prescribed limits.

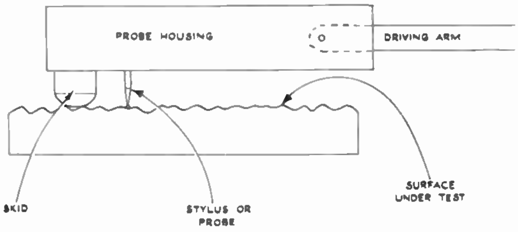

Fig. 33. Principle of stylus type surface texture comparator.

From the electrical performance point of view coupling flanges fall into two groups:

(a) Those with choke grooves (of arc or circular form) which are frequency conscious, usually having a bandwidth of only ±5–6% of the design frequency, for a v.s.w.r. better than 0·95.[41, 42]

(b) Plain or contact flanges which, providing that flange faces are flat and ensure intimate contact around the waveguide rectangle, will have no frequency restrictions above those imposed by the waveguide size.

mechanical inspection, relying on the electrical test to eliminate all faulty components, which are scrapped with no attempt at rectification. These philosophies may be applied respectively to milled block and dip-brazing production methods and will be economically acceptable, but the application of either extreme philosophy to other production techniques may well prove uneconomic and frustrating.

If the hypothetical component mentioned in the second paragraph of this section is considered, and it is assumed to be an assembly fabricated by brazing, for example, it is likely to prove uneconomic to employ the precise, almost microscopic, examination normally associated with milled block components for its inspection. The very thorough examination postulated to discover small flaws in the component might be construed as necessary because the inspector failed to be sufficiently alert or precise in his initial examination. The problem then reduces to one of degree, the level of inspection required being a function of the designer's correctness in estimating the electrical effects of his specified mechanical tolerances. This will not be known to the inspector, and therefore, in order to cover all eventualities the ultimate in inspectional effort and time should be applied to all components. This is obviously unrealistic and uneconomic, as it will only pay dividends on a very small percentage of components, and will still fail to detect those which may be perfect mechanically, but unacceptable electrically.

The inspection method for components produced by most manufacturing techniques will fall somewhere between the two extreme philosophies mentioned, and requires sensible co-ordination of mechanical inspection and electrical testing. Even when the philosophy of minimum inspection is adopted it will still be essential to carry out adequate mechanical interchangeability checks.

15. Acknowledgments

This paper is published with the permission of the Ministry of Aviation, but any opinions expressed are the author's own.

The author gratefully acknowledges assistance and advice from many colleagues in Government Establishments and in Industry.

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Based on a Dissertation accepted for the Diploma of Battersea College of Technology in Microwave Physics.

REPORT OF THE 35th ANNUAL GENERAL MEETING

The Institution's Annual General Meeting, the twenty-seventh since Incorporation, was held at the London School of Hygiene and Tropical Medicine on Wednesday, 11th January, 1961.

The Chair was taken by Professor Emrys Williams, Ph.D. (Vice President) and when the meeting opened at 6.5 p.m. 72 corporate members had signed the Minute Book. In addition, over 50 non-corporate members were present.

The Secretary, Mr. Graham D. Clifford, first read the notice convening the meeting, which had been circulated to members and published in the November 1960 *Journal*. The meeting then proceeded to the Agenda as follows:—

1. To confirm the Minutes of the 34th Annual General Meeting held on the 2nd December, 1959.

The Secretary stated that the Minutes of the last Annual General Meeting were published on pages 737–739 of the December 1959 *Journal* and that no adverse comment had been received. The Chairman's proposal that those Minutes be signed as a correct record of the proceedings was approved unanimously.

2. To receive the Annual Report of the Council for the year ended 31st March, 1960.

Before formally presenting the Annual Report, Professor Williams conveyed the regrets of the President, Professor Eric Zepler, that due to his recent serious illness he was unable to attend the meeting. All members present signified their desire to be associated with a message of good wishes to the President.

Professor Williams then proceeded to the presentation of the Council's Report (published in the December 1960 *Journal*) in the following terms:

"Most of you were present last April at an Extraordinary General Meeting when a unanimous resolution was passed authorizing the Council to petition for a Royal Charter of Incorporation. As stated in the Annual Report, the Officers of the Institution who comprised the Petitioners have given a great deal of time to this objective. The result of their endeavours will be conveyed to members immediately a decision is made known. In the event of the Petition being successful the Charter will itself name those members of the Institution who are to be the President, Vice Presidents, ordinary members of Council, and Honorary Treasurer. For this reason the Council felt that it was unnecessary to elect new Officers of the Council at this meeting. Notice to this effect was given in the November 1960 *Journal* and it is understood that all corporate members are agreeable to this course of action.

"Meanwhile, I would ask members to note from the Annual Report under review the progress which has been made in every facet of the Institution's activities. In a year's time it is hoped to make known the result of negotiations which are now taking place for the acquisition of a more extensive Institution building. We also hope to secure the approval of corporate members to the establishment of a Research Scholarship Fund. This latter point is but one of several developments which the Council is undertaking in an endeavour to make more useful the purpose and work of the Institution.

"Our progress can be assured by the continual growth of membership, and for the last twenty-five years we have been able consistently to report an increase. This has not easily been achieved because membership is dependent upon interpretation of the educational policy of the Institution and satisfying the high standards of examination. The reports of the Education and Examinations Committee are therefore valuable aspects of the Institution's work.

"Some of the ways in which the Institution advances the science of radio and electronics are shown in the reports of the Technical and Programme and Papers Committees, as well as in the activities of the specialized Groups. Most of these activities are reported in the Institution's *Journal* and once again we are able to report a considerable increase in output. The Council believes that the *Journal* can be one of the most effective ways of implementing the objects of the Institution and of giving an even greater service to members and the profession generally. Within the next few weeks† members will be able to see the way in which the Council intends to express its policy on *Journal* publication.

"This policy has, of course, also been reflected in our work over the last fifteen years in arranging particular types of Conventions. The popularity of these meetings is well known and in addition to the comment which has been made in the Annual Report on the last Convention, I refer to the enthusiasm which has met the Council's decision to promote a Convention this year on Radio Techniques and Space Research.

"One regret that we have at an Annual General Meeting is that distance prevents the participation of so many of our members, particularly those overseas.

† Professor Williams spoke with advance knowledge of the new format of the *Journal*. Members will have noted the improvements made as from the January issue.

If we are to exist as a corporate body, we have more to do in the development of new Sections in this country and in the Commonwealth countries. Our record is, I think, outstanding in what we have already done in this direction, and I am sure that our policy regarding *Journal* and other publications will do much toward encouraging the corporate spirit in that we can see in the pages of our *Journals* what is happening elsewhere, even though we do not have as many opportunities as we would like of welcoming our members throughout the world.

"Our Library work is but another example of the Institution's services, and overall—and I think it dominates most of our reports—is this feeling not only of providing services, but also of receiving them. All that I have spoken about and all that has been written in the Annual Report would be impossible without the help of the many members who assist the Institution by service on local and standing Committees and in representing the Institution in the work of other bodies. The satisfactory nature of this report is due in no small measure to their endeavours.

"The report of the Finance Committee will be dealt with by our Honorary Treasurer, Mr. G. A. Taylor.

"I welcome this opportunity of thanking all members who help the Institution and have much pleasure in proposing the adoption of the Thirty-fourth Annual Report of the Council."

The proposal was seconded by Colonel J. P. Martindale (Member), who referred especially to the work done by the Officers of the Institution. Colonel Martindale expressed the view that the report should be adopted with acclamation as a token of appreciation of the work done by the General Council during the year under review. The Report was then put to the vote and adopted unanimously.

Dealing with the next four items on the Agenda—the election of President, Officers, ordinary members of Council and the Honorary Treasurer—Professor Williams stated that he had already explained why the Council did not wish to proceed in the matter of new elections. All members had signified their approval and Professor Williams therefore called upon the Honorary Treasurer, Mr. G. A. Taylor (Member), to deal with Item 7 of the Agenda.

7. To receive the Auditor's Report, Accounts and Balance Sheet for the year ended 31st March 1960.

Mr. George Taylor, Honorary Treasurer, presented the Accounts by first paying tribute to the members of the Finance Committee who had the responsibility of now handling income and expenditure which together totalled some £100,000, a figure which Mr. Taylor believed might well be doubled within the next few years. The Institution's Accounts for the year under review showed quite clearly the excellent progress being made, and Mr Taylor said that if members had read the history of the Institution, published under the title "A Twentieth Century Professional Institution"†, they would readily appreciate the tremendous efforts made to bring the Institution to its present financial position. Mr. Taylor continued: "The report of the Finance Committee published in the December *Journal* gives an overall picture of the Accounts under review. As Treasurer of the Institution, however, I would like to take this opportunity of giving a little more detail on one or two points.

"Dealing with income, it will be seen that there was a satisfactory increase in nearly all items. The sales of publications, including *Journals*, however, showed a slight decrease, despite the fact that subscriptions for current *Journals* are continually increasing, particularly from Commonwealth and overseas countries. This slight decrease is explained by the fact that most of the Institution's publications up to the end of 1958 are now completely exhausted, and the demand can no longer be met.

"Referring now to Expenditure, I said in my report last year that we must face the prospect of some increase in Administration Expenses. I made particular mention of the Institution's Pension Scheme for its staff and it will be seen that to a limited extent this arrangement has been implemented. I must, however, emphasize that this item will continue to grow. The increase in salaries is occasioned by the additional staff engaged to cope with the ever increasing demands of membership activity.

"The cost of producing the Institution's *Journal* and report rose considerably, but as will be seen from the Accounts, revenue from advertising greatly helped to offset this expenditure.

"I now come to the question of Section Expenses. The Annual Report will indicate the way in which the Section Committees are now giving consideration to the fact that all the Institution's Sections, both at home and overseas, must have an increased grant to cater for their local activities.

"So far as our Balance Sheet is concerned, older members of the Institution must view with considerable satisfaction the way in which we have been able to build up our Reserve Account and the development of our Investments.

"We must not ignore the substantial help which has been given to the Institution by the donations from members and companies and which are allocated to the Building Appeal. The Annual Report will have indicated the urgency of the Institution acquiring

† "A Twentieth Century Professional Institution—The Story of the Brit.I.R.E." Published by the Institution, price 30s. post free.

adequate premises to provide a Lecture Theatre, further Library rooms, and office accommodation to cope with increased administration work."

Mr Taylor concluded by referring to the fact that although the last Annual General Meeting had indicated unanimous support for an increase in subscriptions, such a step had not yet been taken. The reasons for not implementing this decision were given in the Annual Report, but Mr Taylor felt sure that all members would readily appreciate that continuation of the Institution's work and services would depend upon an increase in subscription revenue. Arrangements for securing these increases would, of course, be placed before members within the next six months.

Mr Taylor then formally proposed the adoption of the Accounts and Balance Sheet for the year ended 31st March, 1960, which was seconded by Mr. L. F. Mathews (Member), and carried unanimously.

8. Appointment of Auditors

Professor Williams referred to the assistance given by the Institution's Accountants, Messrs. Gladstone, Jenkins and Company, whose advice on the Institution's finances was always appreciated. The proposal that they be reappointed as Auditors was approved and it was also agreed that the matter of remuneration should be at the discretion of the Council of the Institution.

9. Appointment of Solicitors

The Chairman stated that he was pleased to welcome to the meeting Mr. Gray Hill and to have the opportunity of thanking him for his work during the past twelve months, particularly in connection with the preparation of the Charter Petition. The proposal that Messrs. Braund and Hill be reappointed as Solicitors to the Institution was approved unanimously.

10. Award of Premiums and Prizes

Professor Williams said that this item on the Agenda always gave great pleasure, particularly to the Chairman, and he was glad to have the opportunity of congratulating personally several of the recipients of Premiums and Examination prizes for 1959.

Premiums and Awards† were then presented to Mr. D. C. Brothers and Mr. K. G. Freeman (Associated Rediffusion Premium), Mr. P. B. Helsdon (Heinrich Hertz Premium), Dr. T. B. Tomlinson and Dr. M. Prutton (Charles Babbage Award), and Mr. I. J. P. James (Marconi Award).

The recipients of the Brabazon Award (Messrs. D. M. Makow, R. R. Real, H. R. Smyth and S. K. Keays) were resident in Canada and Professor Williams said that arrangements were being made for the presentation of their award later this year at a meeting of the Montreal Section.‡

Mr. T. C. R. S. Fowler, winner of the McMichael Premium, was also unable to be present and in this case the presentation will be made on behalf of the President at a meeting of the South Western Section in Bristol.

11. Any other business

The Secretary stated that he had not received notice of any other business and the Chairman then declared the 35th Annual General Meeting of the Institution at an end.

Immediately following the Annual General Meeting, the Annual General Meeting of Subscribers to the Institution's Benevolent Fund was held. A report of the proceedings will be published in the March *Journal*.

After the conclusion of the two business meetings, Mr. L. H. Bedford, C.B.E., M.A. (Past President) took the chair for the presentation of a paper on "Multi-layer Switching Devices" by Dr. D. F. Taylor.

† A full list of the winners of Premiums and Awards was published in the *Journal* for September 1960 (page 642) and the Examination Prize winners were listed in the Annual Report (*Journal* for December 1960, page 896).

‡ The intended visit of an officer of the Institution to Montreal was referred to on page 40 of the January *Journal*.

U.D.C.621.318.52

Sealed Contact Relays

By

J. G. BANNOCHIE, M.Sc.

AND

R. A. E. FURSEY, B.Sc.

Presented at the Symposium on New Components, held in London on 26th–27th October 1960.

Summary: The construction and properties of dry reed and mercury contact relays are discussed. The dry reed relay provides gold plated contacts with a single make action. It operates in a magnetic field of about 100 ampere turns and releases at about 40 ampere turns. It can be made to operate in about 1 ms with little contact bounce. The contacts have low contact resistance and can handle up to 15 VA at a maximum current of ¼ A. The mercury contact relay is a polarized relay with a single changeover action in which the contacts are wetted with mercury. Typical operate–release values obtained by adjustment of polarizing permanent magnets are 60 and 40 ampere turns respectively. It operates in less than 1 ms with complete freedom from contact bounce. The maximum load is 25 VA with a maximum current of 5 A. The relays find their main applications where contact reliability is essential and some applications of special interest are briefly described.

1. Introduction

The growth in complexity of modern electronic equipment makes it particularly desirable that the components used should have a long life and that they should require a minimum of maintenance. For relays the provision of sealed contacts can be a solution to the problem of component reliability. The development of sealed contacts has resulted in the production of the dry reed relay,[1] and the mercury contact reed relay.[2, 3] These relays are shown schematically in Figs. 1 and 2 and the actual inserts and assemblies in Fig. 3. Protection from the adverse effects of environment is achieved in these relays by supporting the contacts on members of magnetic material which are sealed into a glass envelope containing a protective atmosphere. In addition, the mercury contact relay is provided with mercury-wetted contact surfaces that minimize the effects of electrical erosion. The magnetic members overlap slightly and are separated by a small gap so that when an operating coil surrounding the envelope is energized the resulting magnetic field causes the contacts to be attracted together. Considerable simplification of the relay mechanism is thereby achieved which results in faster operating speeds than are possible with conventional relays.

The dry reed relay was first developed over twenty years ago by the Bell Telephone Laboratories of New York. An early form of the mercury contact relay[2] was developed somewhat later and the balanced polar form was first described in 1953.[3] The dry reed relay has found increasing uses in the communication field and the Western Electric Company have several automatic manufacturing units each capable of producing a million units a year, at a reported cost per relay insert comparable with two nickel silver leaf spring contacts of the conventional relay.[4] The production of mercury contact relays is believed to be much less. The relays are also manufactured by other companies in the U.S.A. and now in Britain.

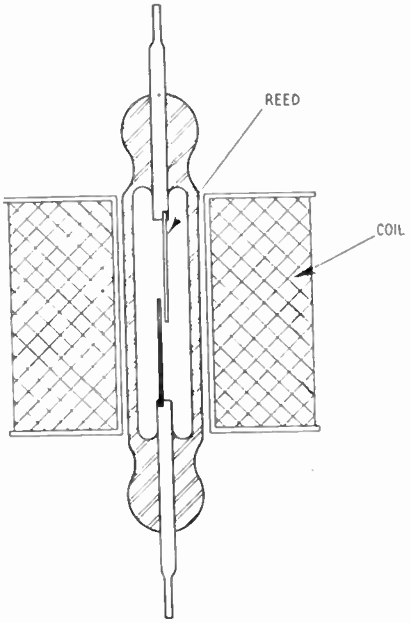

Fig. 1. Dry reed relay.

The sealed contact reed relays with which this paper is concerned relate to relays in which the contacts and supporting members alone are sealed. Any attempt to produce a sealed contact relay by enclosing a whole

† British Telecommunications Research Ltd., Taplow Court, near Maidenhead, Berkshire.

conventional relay within a hermetically sealed enclosure must be deprecated. Even if it can be argued that mobile dust particles are thus excluded other factors, such as the presence of organic vapours within this sealed enclosure, are likely to be highly detrimental to contact life and behaviour.

2. The Construction of Sealed Contact Relays

In the dry reed relay (Fig. 1) two flat reeds of magnetic nickel iron alloy are supported parallel to each other by sealing into opposite ends of a glass envelope so that their free ends overlap slightly and are separated by a small gap. The free ends of the reeds are plated with a precious metal—in the authors' experience preferably gold—which is partially diffused into the reed during a preliminary magnetic annealing process. On energizing the operating coil the resulting magnetic field causes the reeds to be attracted together. The dry reed relay thus provides a single "make" action.

In the mercury contact relay (Fig. 2) a flat reed of magnetic nickel iron alloy is welded to a support tube which is sealed into one end of the glass tube. Fixed pole pieces of magnetic alloy carrying platinum ball

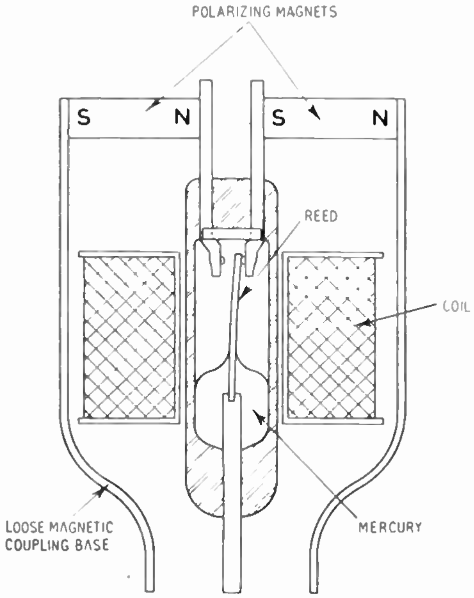

Fig. 2. Mercury contact reed relay.

contacts are sealed into the opposite end of the glass tube so that the reed lies between them and slightly overlaps their ends. The reed is grooved with capillary channels and is plated with a metal such as nickel, which is capable of being wetted by mercury. Mercury is introduced into the glass tube during manufacture and caused to wet the reed so that by means of the capillary channels the entire surface of the reed is fed with mercury. In use small permanent magnets are soldered to the pole pieces and have a loose magnetic coupling to the reed. The reed moves to one or other of the pole pieces and so partially completes the magnetic circuit on that side. Energizing the operating coil with current of the appropriate polarity will change the direction of reed magnetization and cause the reed to move over to the

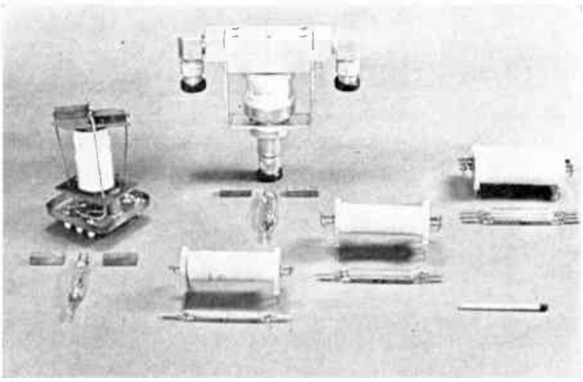

Fig. 3. Sealed contact reed relay inserts and assemblies.

opposite pole piece. It will remain there with the coil unenergized until a current of opposite polarity is passed through the coil. The polarized mercury contact relay thus provides a single "changeover" action with mercury-wetted contacts. This action is a "make-before-break" due to the drawing out of a mercury bridge across the narrow gap. This each-side-stable operation is achieved with balanced strength of the two permanent magnets; suitable adjustment of the magnet strengths can vary sensitivity and secure either each-side-stable or one-side-stable operation.

2.1. *Materials*

The most suitable material for the reeds is considered to be a 50–50 nickel-iron alloy. The expansion characteristics of this material match those of lead glass so that a one-piece forging can be used for the reeds of the dry reed relay inserts. In an earlier version of the dry reed relay insert and in the mercury relay insert the reed is welded to a support tube. The material for the support tube, and for the pole pieces of the mercury contact relay insert must be magnetic but can be chosen to match the expansion characteristics of the softer borosilicate glasses.

Gold is chosen for the contacts of the dry reed relay. It is soft and the contacts can be "run-in" to give a very low contact resistance. The life testing experience to date appears to justify the choice of gold as a contact material. Hydrogen is probably the best protective atmosphere but nitrogen appears to be an acceptable substitute in the case of the forged reed relay where hydrogen filling is impossible.

2.2. *Manufacture*

Many of the processes in manufacture are common to both relay inserts. The reeds are formed by cold working and must be annealed in hydrogen to develop their magnetic and elastic properties. This annealing is preferably a two stage process; a high temperature annealing is given to restore the properties and to de-gas the parts prior to sealing, the contact areas are then plated, and a low temperature annealing partially diffuses the contact plating into the base metal and further improves the properties. After annealing the parts are sealed into the glass tube, which is filled with a protective gas.

All the processes in manufacture must be carefully controlled. Starting with the forming of the reed, the contact surfaces must be flat and smooth for the dry reed insert, and properly grooved in the case of the wetted reed of the mercury contact relay insert. The annealing temperatures must be controlled to ensure reproducible properties and to produce the required degree of diffusion of plating. The plating thickness must also be kept constant. Above all, due attention must be paid to cleanliness, because any contamination will be sealed permanently within the glass tube. The alignment of the reeds, the overlap and the gap are all important factors in determining the final characteristics of the relay. The means of sealing the reeds within a glass tube must accurately preserve the spacing and alignment and must produce seals of constant size and location to enable reproducible properties to be obtained. Flame sealing is unsuitable and electrically heated coils of wire surrounding the tube are used instead. When the parts are positioned, the heater coils are energized and their radiant heat softens the ends of the glass tube which are then drawn inward by surface tension until the glass touches and wets the material of the reed support, so making the seal. An appropriate heating cycle is given to anneal the glass and produce substantially strain free seals. The sealing operation is carried out in an atmosphere of nitrogen to prevent oxidation.

2.2.1. Dry reed relay inserts

In the dry reed relay insert it is found that the ampere-turns required to just operate increase rapidly with increase in gap dimension. For a constant gap there is an optimum overlap for maximum sensitivity, and this permits reproducible properties to be obtained. In manufacture the reeds are positioned with the glass tube vertical and the overlap is pre-set. The reeds are locked together by an external electromagnet and the top seal is made. The magnetic lock is then released, the desired gap set and the lower seal made. A gap of 0·010 in. and the optimum overlap of 0·050 in. gives an operate value of about 100 ampere-turns and a release value of about 40 ampere-turns. When one piece forged reeds are used the insert is automatically filled with the nitrogen used in the sealing operation. If welded reeds are used the insert can be filled with dry hydrogen or nitrogen and sealed shut by welding.

2.2.2. Mercury contact reed relay inserts

In the mercury contact relay insert the pole pieces carrying the platinum ball contacts are carefully positioned and sealed into one end of the glass tube with the contacts about 0·020 in. apart. The reed is then positioned between the contacts and the overlap is set so that contact occurs near a node in the vibration of the reed. The glass seal to the support tube is then made in an atmosphere of nitrogen. With gaps of the order of 0·005 in. between reed and contacts, operate values of 100 ampere-turns are achieved in the assembly with fully magnetized polarizing magnets. Minor displacements of the reed towards one contact can be neglected because the magnets are adjusted to give the final operate/release values. After assembly the insert is evacuated via the reed support tube and baked out. Mercury and hydrogen are introduced and the insert is sealed by welding the support tube. The insert is then heated, and in the presence of the reducing gas the clean surfaces of the platinum and nickel, which are very slightly soluble in mercury, become wetted.

3. Properties of Sealed Contact Relays

The most important electrical properties of the dry reed relay and the mercury contact relay are their contact reliability and high speed of operation.

Typical properties of both dry reed and mercury contact relays are set out in Table 1.[5] The values given in this Table and in the text refer to standard production models whose dimensions are large compared with modern electronic components. Dry reed relay inserts $\frac{3}{4}$ in. long and $\frac{1}{8}$ in. in diameter and mercury contact inserts $1\frac{3}{4}$ in. long and $\frac{5}{16}$ in. in diameter are now being produced.[6, 7] These have increased sensitivity but reduced power handling capacity.

3.1. *Operate and Release Values*

The operating characteristics of the reed relays depend upon a number of properties. These include the magnetic and elastic properties of the reed materials, the reed dimensions, their gap and overlap, the thickness of the plating for the contacts and the nature of the supports at welds and at the glass-to-metal seals.

Table 1

Typical Sealed Reed Relay Characteristics[5]

Characteristic†	Dry reed relay	Mercury wetted reed relay
Contacts	Single pole Single throw Normally open Snap action	Single pole Changeover Make before break Snap action
Gas filling	Nitrogen 1 atmosphere	Hydrogen 10 atmospheres
Contact surface	Electroplated rhodium or gold	Fixed: Pt balls Reed: nickel plate
Open contact breakdown	1·3 kV	About 4 kV
Maximum contact ratings	500 V 500 mA 15 watts‡	500 V 5 A 25 watts‡
Operate/release ampere turns	160/120 to 85/30	+ 60/+ 30 to + 30/− 30
Operate time§	1–1·3 ms	1 ms
Bounce time§	0·3 ms	None
Release time¶	0·15 ms	0·8 ms
Max. operating frequency	400 c/s	350 c/s
Dimension of insert	2¾ in. long ¼ in. diam.	2½ in. long ⅜ in. diam.
Advantages‖	Mount in any position, inexpensive, fast, reliable	No contact bounce, high current capacity, changeover contact, fast, reliable
Disadvantages	Single make contact, some contact bounce, large size	Costs more, upright mounting, pressurized inserts need careful mounting

† May vary considerably with model and manufacturer.
‡ For long life.
§ With twice the "just operate" ampere turns in a standard 10 000-turn, 1000-ohm coil.
¶ When standard test coil is open-circuit.
‖ Both are fast, reliable, have long life and handle low voltage.

3.1.1. Dry reed relays

The mass of the parts for the dry reed relay should be kept small to limit bounce. The reeds also must be sufficiently stiff to prevent contact closure due to external vibration. The ampere-turns required to just-operate, increase with increase in gap dimensions. "Overlap" influences operate/release ratio as does the thickness of contact plating. Too large an overlap causes magnetic saturation effects which reduce the efficiency of the relay. Fortunately there is an optimum for the overlap which permits reproducible properties to be obtained in manufacture. Practical values are about 100 ampere-turns to operate and about 40 ampere-turns to release. This is achieved with a gap of the order of 0·010 in. and an overlap of 0·050 in.

These values of ampere-turns relate to measurements in a simple test coil but sensitivity can be improved by completing the external magnetic circuit. The ampere-turns required to operate and release the relay are unchanged by temperature variations between −40° C to +140° C.

3.1.2. Mercury contact reed relay

In the polarized mercury contact reed relay the pole pieces bearing the platinum contacts are fixed and in operation the reed armature moves to them. The reed must therefore be flexible and the gap small. An excessive gap or overstiff reed prevents the correct each-side-stable action of the device. The gap however, must be wide enough to break the mercury bridge which is drawn out from the contact as the reed moves away. This break must take place shortly after the reed reaches the opposite contact. The overlap is set so that the contact occurs near to a node in the vibration characteristic of the reed. This condition is given priority over considerations of a purely magnetic nature. The gaps between reed and pole piece contacts are of the order of 0·005 in. By adjustment of the polarizing magnets "operate/release" values may be varied. Values of 60 ampere-turns to operate and 40 ampere-turns to release are typical for a one-side-stable relay.

3.2. *Speed of Operation and Contact Bounce*

3.2.1. Dry reed relays

When the electromagnetic field applied to a reed relay builds up, both reeds deflect and a point is reached where the mechanical force tending to keep them apart equals the magnetic force tending to close them. Further increase in the electromagnetic field causes further mechanical deflection until the gap is almost closed. A point is now reached where due to the reduced gap, the increase in the magnetic field accelerates rapidly while the restraining spring tension is still building up uniformly. The result is a rapid snap-action closure of the contacts. For a given insert the speed of operation will depend on the rate of increase of current in the coil and so is dependent on the coil constant N^2/R, where N is the number of turns and R the resistance. When the energizing current is just greater than the just-operate value, the operating time will depend markedly on the coil constant. Increasing the energizing current brings an increase in operating speed which now tends to be less dependent on the coil constant. The operate speed does not increase appreciably with energizing current in excess of three times the just-operate value. Typical reed relays have an operate time of a half to one millisecond when driven at this level. The increase in magnetic force due to the closing of the contact gap causes the reeds to accelerate and the resultant momentum produces contact bounce upon contact closure. The duration of this bounce increases with increase in energizing current. Minimum total "operate time plus bounce time" occurs when the relay is energized with a current of about two and a half times the just-operate current as shown in Fig. 4. When energized with alternating current the situation is complicated by the excitation of reed resonances which may cause excessive bouncing at certain frequencies. Reasonable square wave operation however can be achieved at most frequencies up to 300 to 400 c/s. This is accomplished by driving the relay with a sine wave current of half the relevant frequency. The release time is typically 80 to 150 microseconds for reed relays in the usual 10 000 turn, 1000 ohm coil with simple open circuit release.

3.2.2. Mercury contact reed relay

The speed of operation of the mercury contact reed relay depends on the coil constant, the position of the coil relative to the working gap and on the bias adjustment of the two permanent magnets. An operate time of just under 1 millisecond can be achieved and a release time, for a one-side-stable relay, of down to 0·75 millisecond. Due to the bridging of the mercury upon operation of the relay, there is a period of about 0·2 millisecond when all three contacts are in contact. This make-before-break operation, while useful in some applications, is a drawback in others.

3.3. *Contact Properties*

3.3.1. Contact resistance at low voltage

Conventional relays often give trouble when handling voltages which are too small to break down the insulating surface films which may appear on unenclosed contacts particularly when they have not been operated for some time.

This problem does not arise when the contacts are enclosed and are of suitable material—such as gold, or are mercury wetted. The resistance at the contacts in these cases is very small even at low signal levels and is negligible compared with the 20 to 30 milliohms resistance of the reeds themselves. The snap action of the dry reed relay results in a contact force of over 40 grammes at the "just-operate" current and at least 30 grammes for all reasonable holding currents. This force between clean contacts in an inert atmosphere is responsible for their excellent behaviour. Contact resistance is normally measured with a current of 10 mA from a 100 mV d.c. source.

Due to the large thermo-electric e.m.f. of 35 microvolts per deg C that exists between copper and the nickel iron alloys used, care must be taken to avoid temperature differences between the ends of the relays when used in low-level d.c. circuits.

3.3.2. Contact rating

Recommended maximum voltages, currents and load ratings for long life are shown in the Table. These apply to purely resistive loads and contact protection by means of resistor-capacitor networks, rectifiers, etc., should be used to suit the loading

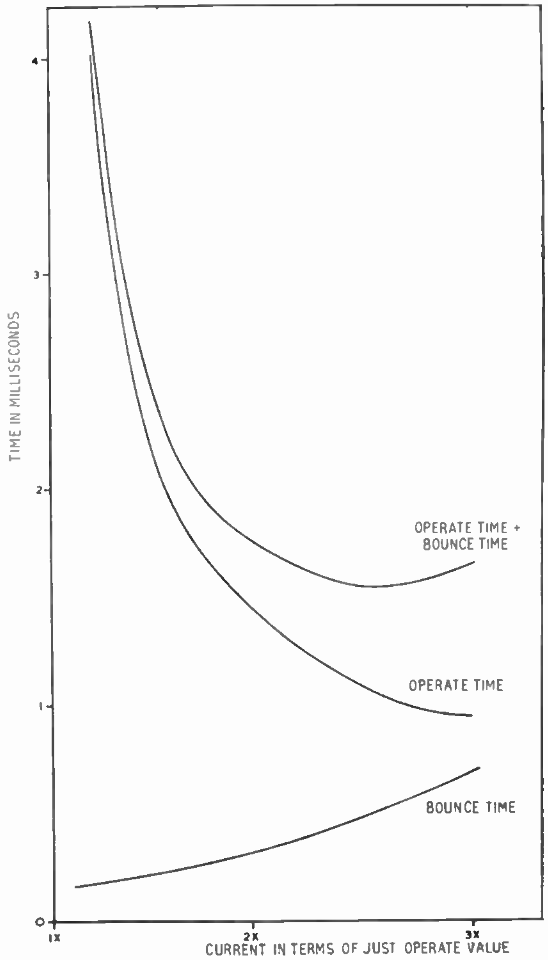

Fig. 4. Variation of operate and bounce time with energizing current.

conditions. Accelerated life tests on dry reed relays switching 250 V d.c. 100 mA into resistive loads have shown that most relays will achieve 100 million operations before the overall resistance increases to more than 50 milliohms. Contact failure is heralded by a marked increase in contact resistance produced by a build-up in the gap of erosion products which finally bridge the contacts.

Mercury contact relays are rated at 100 million operations at full load by their manufacturers. The operating conditions are reported to show a small change due to wear, as indicated by an increase in operating current.

3.4. "*Switching-Time*" *of Mercury Contact Reed Relays*

A valuable property of these wetted type reed relays is the exceedingly short time taken for the contact resistance to fall from open circuit value to closed circuit value when the actual contact is made. This is not to be confused with the operate times dealt with previously in which consideration was given to the time that elapses between energizing the coil and the subsequent closing of the contacts. This short "switching-time" is due mainly to the fact that when contact is made between two clean mercury surfaces the resistance falls quickly to practically zero. With a pair of conventional dry contacts, the contact resistance is relatively high on first lightly touching and then falls comparatively slowly while contact pressure is building up. This property of short switching-time has permitted application of the relay to the generation of pulses with exceedingly short rise time.[8] In this application, a charged capacitor or length of coaxial cable is switched via the relay to the output transmission line. In the application described it was found that by keeping the applied voltage below 10 V to avoid voltage breakdown across the gap prior to actual closure, pulses with rise times of one millimicrosecond were produced.

The high-speed capability of these relays permits pulse repetition rates of several hundred pulses per second to be easily obtained.[7]

4. Applications

Sealed contact relays will find their main application where contact reliability is essential. The reed relay inserts require only the application of a magnetic field for operation. There are therefore numerous ways of employing these inserts in relay devices and in this survey only examples from the various types of application can be mentioned. Examples have been chosen where technical advances have been made possible by the use of reed relays.

4.1. *Dry Reed Relays*

In its simplest form a dry reed relay consists of one or more inserts placed in a coil with possibly an external soft iron shield to help complete the magnetic circuit. The contacts will all be make contacts, but it has been shown[9] that even a single make relay can provide a useful logic and memory unit when provided with a multiple coil. Computers built around these units have operating speeds intermediate between those of electronic and existing electro-magnetic computers.

Break contacts and latching action relays are produced by the addition of polarizing coils or permanent magnets. This type of latching relay has been taken a stage further by Bell Telephone Laboratories who have combined a dry reed relay with a magnetically hard ferrite to give a device—the Ferreed[10]—in which the state of the contacts is controlled by the magnetic state of the ferrite. Although the operate time of the unit is about 1 millisecond it can be controlled by a pulse of a few microseconds duration and requires no holding current. It is therefore eminently suitable for switching in electronically controlled exchanges.

Reed relay inserts lend themselves readily to coaxial construction by using the inserts as the inner conductors and mounting the operate coils outside the outer conductors.

In one of their first uses outside the telephone industry dry reed relay inserts were operated by moving permanent magnets rather than by coils as this provided a very convenient method of fluid metering through the walls of sealed high pressure systems.

4.2. *Mercury Contact Reed Relays*

The applications of mercury contact relays have not been quite so diverse as those of dry reed relays. It is naturally more expensive to produce and being essentially a balanced polar device is usually supplied as a complete relay by the manufacturers with its magnets adjusted to give the required operate and release values.

In addition to its previously mentioned uses as a coaxial relay and for producing fast rise pulses it is generally used when a fast, sensitive bounce-free relay with long life is required and its make-before-break action and need to be kept upright are not disadvantages.

5. Conclusions

In addition to their contact reliability, the sealed contact relays are fast, robust, fairly compact, and of reasonable sensitivity. The properties are remarkably constant with temperature in the range $-40°$ C to $+140°$ C.

The single make action of the dry reed insert does not necessarily limit its application. Several inserts can be combined with one coil and break or latching action can be achieved by the use of permanent magnets.

The relays possess low contact resistance, but the dry reed insert contacts should not be subjected to current greater than $\frac{1}{4}$ A. In complex systems the dry reed inserts can be used for light duty switching applications in conjunction with mercury contact relays for the heavier duty circuits.

Because of the particular properties of these relays, their application can be considered as a useful intermediate stage between the older slow electro-mechanical switching practice and future wholly electronic switching techniques.

6. Acknowledgments

The authors would like to acknowledge the skill and ingenuity of Mr. R. A. Mills in solving the many intricate mechanical problems arising in the work of making and testing relay inserts and assemblies.

The permission of the McGraw-Hill Publishing Company to reproduce Table 1 from an article[5] by one of the authors (R. A. E. F.) is acknowledged with thanks.

Acknowledgment is also due to the Director of Research, British Telecommunications Research Limited, for permission to publish this paper.

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News from the Commonwealth Sections

Institution activities in Canada and India were reported in last month's Journal. *Members visiting Commonwealth Countries and wishing to attend local section meetings or meet local members are invited to advise the Institution in London when letters of introduction will be given.*

AUSTRALIA

With the growing number of British and European companies setting up development laboratories at their factories in Australia, Brit.I.R.E. membership has increased considerably in the past few years. Many members are also employed in the installations associated with the Woomera Rocket Range and in Australian Government Departments. Among the latter is Mr. R. G. Kitchenn (Associate Member) formerly a member of the General Council of the Institution and of the Programme and Papers Committee; he has also contributed papers to the Brit.I.R.E. *Journal*.† Mr. Kitchenn is now with the Central Administration of the Australian Postmaster General's Department, responsible for trunk planning. Since 1958 he has been Honorary Secretary of the Telecommunication Society of Australia. This is a body of engineers within the P.M.G.'s Department (similar to the Institution of Post Office Electrical Engineers of London) which was formerly known as the Postal Electrical Society of Victoria; the Society publishes regularly *The Telecommunication Journal of Australia*.

As members will know, the Institution enjoys very cordial relations with the Institution of Radio Engineers, Australia, both in the reprinting of papers and in facilities provided for visiting members. This year the Australian Institution's Convention will be held in Sydney from 20th–25th March and will be a comprehensive one dealing with the whole field of radio and electronic engineering rather than with a single theme.

Because of the facilities provided by the Australian I.R.E., the Council has not so far contemplated the establishment of an Australian section of the Brit.I.R.E. Suggestions have been made, however, for the holding of occasional meetings of Brit.I.R.E. members and Mr. K. F. Wellby (Associate Member) has agreed to act as Honorary Secretary for all Australian members. If there is support for the idea, it is proposed that occasional meetings should take place in Sydney, Melbourne and Adelaide and other centres convenient to a reasonable number of members.

Mr. Wellby will be pleased to hear from all members in Australia on this proposal and he may be addressed at his home:—1 Campbell Street, Abbotsford, New South Wales.

† "The design and performance of double-tuned transformers in tandem" (June 1951); "An 8-channel transmitter for an experimental carrier wire-broadcasting system" (August 1951). A short note on Mr. Kitchenn's career was published in the *Journal* for July 1950.

NEW ZEALAND

On behalf of the General Council, the Wellington Section Committee has lodged with the New Zealand Engineers' Registration Board, an application for recognition of the Graduateship Examination and membership of the Institution.

The purpose of the submission is to enable corporate members in New Zealand to be registered as professional engineers. The application will be considered by the Board in March 1961.

CENTRAL AND EAST AFRICA

There has been a notable increase in membership of the Institution in Kenya and Southern Rhodesia. This has been aided, of course, by the growth of the broadcasting and telecommunications systems as well as industrial developments in those areas.

Local members are now anxious to have occasional Institutional meetings.

Informal discussions are being held with members in Nairobi by Mr. Graham Phillips and Mr. D. H. A. Scholey (Associate Members) who are respectively with the Kenya Broadcasting Service and the Directorate of Civil Aviation. It is intended to hold exploratory meetings in order to assess the possible support which might be given to an East African Section. Mr. Phillips is acting as Honorary Secretary in this connection and members wishing to get in touch with him should do so c/o Kenya Broadcasting Service, P.O. Box 621, Nairobi.

In Salisbury, Southern Rhodesia, Mr. R. K. Beaumont (Associate Member) has expressed readiness to act as local Secretary until an exploratory meeting has been held. Members within the Federation who would like to receive further information may write to him c/o P.O. Engineering College, P.O. Box 8182, Causeway, Salisbury.

UNION OF SOUTH AFRICA

South African members who have visited Bedford Square in recent months included both the Chairman of the Johannesburg Section, Mr. M. C. Dickman, and the Honorary Secretary, Mr. G. V. Meij. These visits gave opportunity to discuss ways in which Institution activities in the Union could be extended.

The Section Committee has been giving particular attention during the past year to education matters and has been consulted by the Witwatersrand University on the syllabus of a sandwich course in radio and electronic engineering.

U.D.C. 621.382.333

Silicon Surface Alloy Transistors for High-Frequency Switching and Chopper-Amplifier Applications

Presented at the Symposium on New Components, held in London on 26th–27th October 1960.

By

P. A. CHARMAN†

Summary: These *pnp* silicon transistors are made by an electrochemical process involving optical monitoring of base width and evaporation of aluminium on to controlled areas through a stainless steel mask. Subsequent alloying produces an extremely thin base region which allows the transistor to retain its high-frequency performance down to extremely low operating levels. The combination of low saturation resistance and high turn-on voltage can be used to produce very simple high-speed switching circuits operating over a wide temperature range, and the same characteristics contribute to low drift rates in chopper-amplifier circuits.

1. Manufacturing Techniques

Homogeneous base silicon alloy transistors normally have a cut-off frequency below 5 Mc/s, due to the difficulty of controlling base widths below 0·0005 in., which are necessary for higher frequency operation. Although grown junction and, more recently, mesa type silicon transistors can be made to operate at much higher frequencies, they have inherent disadvantages in certain types of circuit, particularly in the form of high saturation resistance and low reverse base-voltage rating. The silicon transistors to be described were designed to overcome these production and performance problems.

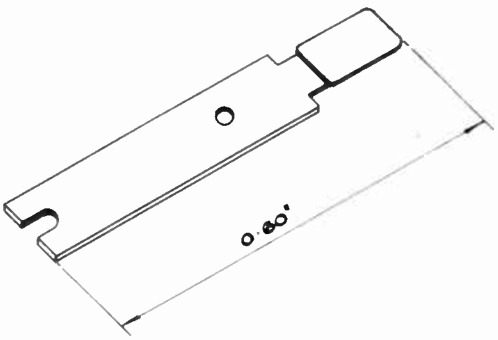


Fig. 1. Blank-tab assembly.

1.1. *Preliminary Assembly*

Silicon blanks, approximately 0·005 in. thick, are prepared by slicing, lapping, etching and dicing pulled silicon crystals doped with antimony to produce low resistivity *n* type material. These blanks are then furnace-soldered in batches to long nickel tabs in a reducing atmosphere (Fig. 1).

1.2. *Electrolytic Jet Etching*

The assembly of silicon on the nickel tab is mounted on a rectangular stainless steel jig (Fig. 2) and accurately located by means of a hole and slot in the tab. A fast rough etching process produces two concentric pits in the silicon which reduce the thickness to about 0·0005 in. over a diameter of 0·020 in. This rough etching process uses two opposed jets of electrolyte and constant current bias source (Fig. 3), the current density and electrolyte composition being set to produce flat-bottomed etch pits. Thickness is controlled by a timer, the process being non-critical at this stage.

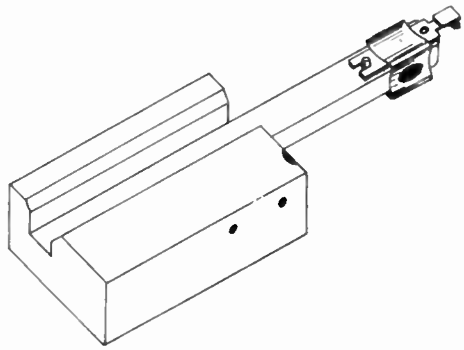


Fig. 2. Blank and tab on work carrier.

1.3. *Precision Etching*

Base width is finally controlled by a precision etching process using the optical transmission characteristics of the silicon as a control (Fig. 4). If the light output of an incandescent lamp is focused on the silicon, the shortest wavelength transmitted is determined by the thickness of the material, and the cut-off is extremely sharp. As the precision etching process proceeds, the silicon becomes thinner and the shortest

† Semiconductors Ltd., Swindon, Wiltshire.

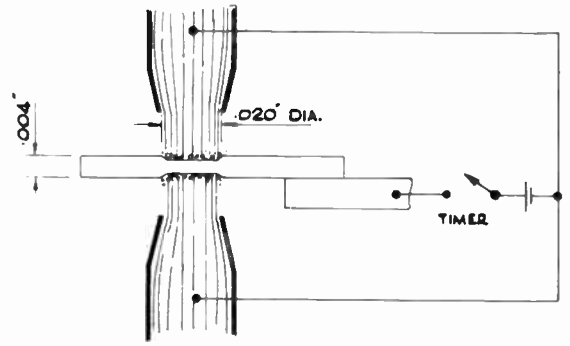


Fig. 3. Rough etch principle.

wavelength transmitted decreases. By using a detector-filter combination whose response is restricted to the shorter wavelengths, the etching process will reduce the silicon thickness to the point where the transmitted wavelength and detector response overlap (Fig. 5), and a rapidly increasing signal is produced. A bridge system compares this with a reference signal obtained from the same light source, and the difference signal is used to shut off the bias current and the jets, giving an accurate control of base width which may be varied in steps by changing the filter and progressively by adjusting the gain of the amplifier between the detector and the bridge. (It is of interest that the early stages of the amplifier use silicon transistors made by this process.)

1.4. *Deposition of Electrodes*

The base width is now in the order of 0·0003 in., and it is necessary to place the aluminium emitter and collector electrodes concentrically in the etch pits. After an ultrasonic cleansing cycle, stainless steel masks are clipped over both sides of the silicon blanks, being located by the pins holding the nickel tab on the work carrier (Fig. 6). These masks have holes appropriate in diameter and location to the emitter and collector. About 100 of these masked blanks are mounted on a drum which is placed in a vacuum box and pumped out with a diffusion pump. Aluminium is then evaporated and deposits evenly through the holes in the masks as the drum rotates. A window in the side of the vacuum box is used for monitoring; as the aluminium deposit builds up on the inside of the window it reduces the Q of a coil on the outside, which allows a Q meter to be calibrated in micro-inches of aluminium. By this technique a uniform film of aluminium of controlled thickness is deposited to form emitter and collector, which have a high degree of concentricity. With such a small amount of material involved, the alloying cycle can be very fast, and this rapid alloying of a uniform thickness of aluminium and silicon over the collector and emitter areas produces extremely thin and flat alloy regions, whose combined thickness is less than 0·000 05 in.

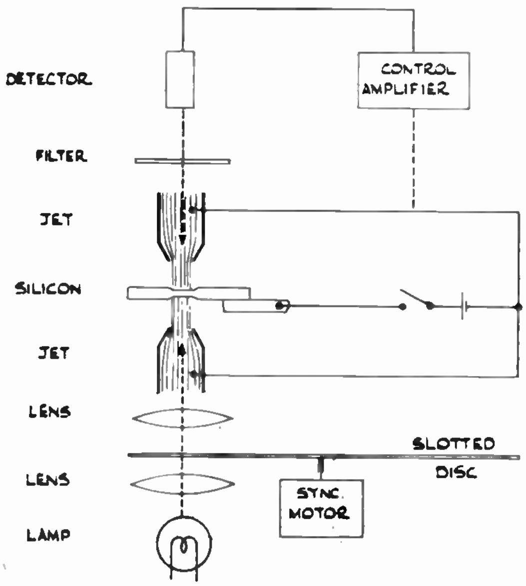


Fig. 4. Precision etch principle.

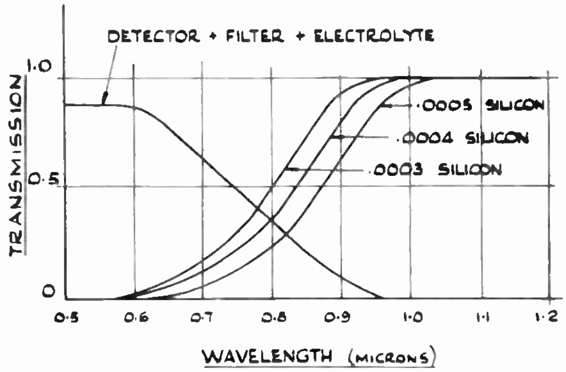


Fig. 5. Infra-red response curves.

1.5. *Final Assembly*

The aluminium electrodes are cleaned and nickel plated before the nickel tab is cut short and welded to the base lead of the transistor stem. Thin nickel wires are soldered to the plated aluminium electrodes, and the free ends welded to the emitter and collector leads (Fig. 7). After a final clean-up process the transistors are baked in vacuum and pass directly from the vacuum chambers into a "dry box" filled with nitrogen having a very low moisture content. In this atmosphere the diode leakage currents are tested and units inside the 0·1 microamps limit have the top caps welded on. Leak testing at 6 atmospheres and complete electrical testing follow.

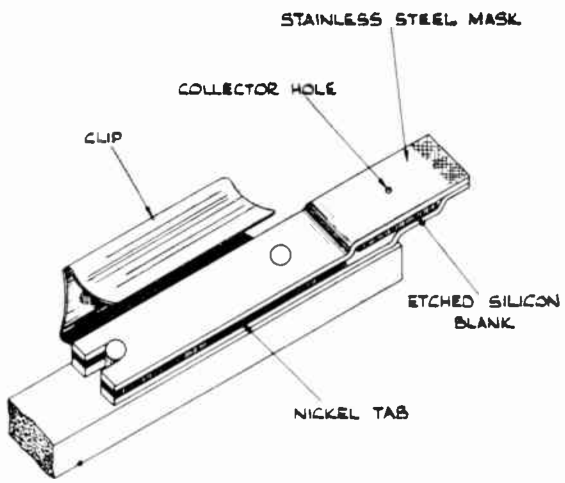


Fig. 6. Masked transistor.

2. Characteristics

The general characteristics of this family of transistors are shown in Table 1.

There are four main types produced by this process.

(i) A switching unit, using low resistivity silicon and thin base, with a 10 volt rating, typical f_1 of 25 Mc/s and a switching specification for directly coupled circuit use.

(ii) "Chopper" types, using very low resistivity material and thicker base.

(iii) A symmetrical unit, made by using similar diameter holes in collector and emitter masks during the evaporating process.

(iv) A general purpose unit, using higher resistivity silicon, with a 25 volt collector rating and a typical f_1 of 20 Mc/s.

The thin homogeneous base region of all four types produces a very low saturation resistance, giving a collector voltage in the 100 mV region when the device is bottomed at 5 mA. Base current begins to flow at 450 mV so that the input characteristic is located well into the linear region of the collector characteristic and directly-coupled operation is possible over the full junction temperature range of the device (Fig. 8). In addition, the breakdown voltage of the base-emitter diode is always well above the maximum collector-emitter voltage rating.

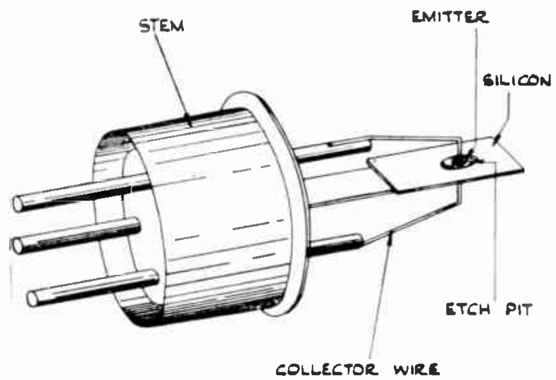
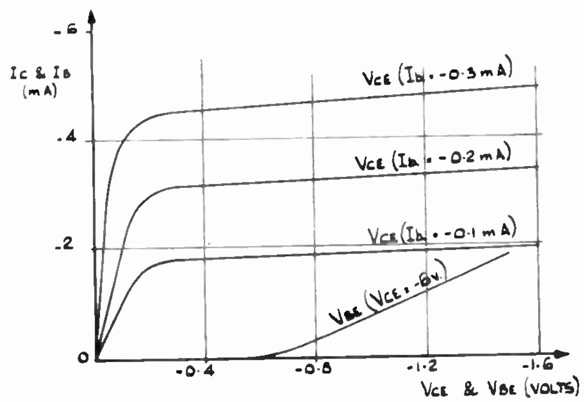


Fig. 7. Complete transistor.

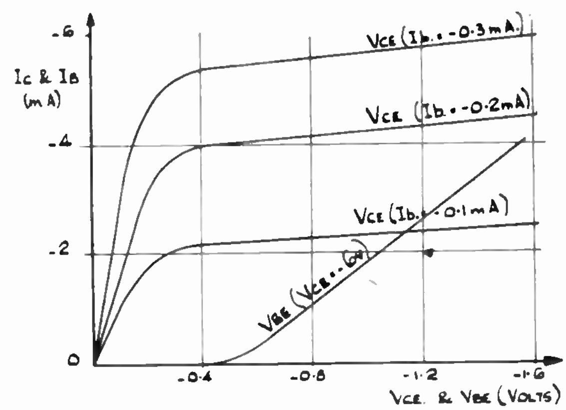
Table 1

Typical Characteristics

Maximum collector-emitter voltage	-25 V	
Collector or emitter diode breakdown voltage	-35 V	
Maximum collector current	50 mA	
Total dissipation at 25° C	150 mW	
Maximum junction temperature	140° C	
Collector or emitter diode leakage currents	10^{-9} amps	
Small signal current gain	15	at 6 V 1 mA
Collector capacitance	7 pF	at 6 V 1 mA
f_1	20 Mc/s	at 6 V 1 mA
Saturation resistance	10 ohms	



(*a*)



(*b*)

Fig. 8. Characteristics of transistor at (*a*) 25° C and (*b*) 125° C.

3. Applications

3.1. *Switching Circuits*

An example of the type of circuit in which full advantage is taken of these characteristics is shown in Fig. 9. This is a decade ring counter which will operate from pulse inputs with up to a 2 Mc/s repetition rate and pulse widths as short as 100 millimicroseconds, in ambient temperatures between $-65°$ C and $+140°$ C. The directly-coupled circuitry eliminates diodes and coupling components, thus minimizing the number of circuit elements and allowing the system to operate from a single 6 V supply.

3.2. *Choppers*

In chopper-amplifier (synchronous switch) applications it is possible to obtain the very low voltage drops normally associated with germanium transistors with the very high input impedance of non-conducting silicon transistors. For the optimum base current of 250 microamps the voltage across the conducting transistor (offset voltage) can be in the order of 1 millivolt; the non-conducting current (offset current) is typically 10^{-9} amperes. These are important fundamentals, but even more important is the change of these parameters with temperature, and the energy content of the transient injected into the output by the switching waveform on the base. Since the physical dimensions of the functioning part of the transistor are minimized, and there is no "surplus" silicon between the collector and emitter, the effect of the change of the physical constants of the semiconductor material with temperature is not so apparent and drift rates as low as 1 microvolt per deg C can be obtained. The very small size and resulting high-frequency characteristics hold the switching transients down to a level which does not mask very small input signals.

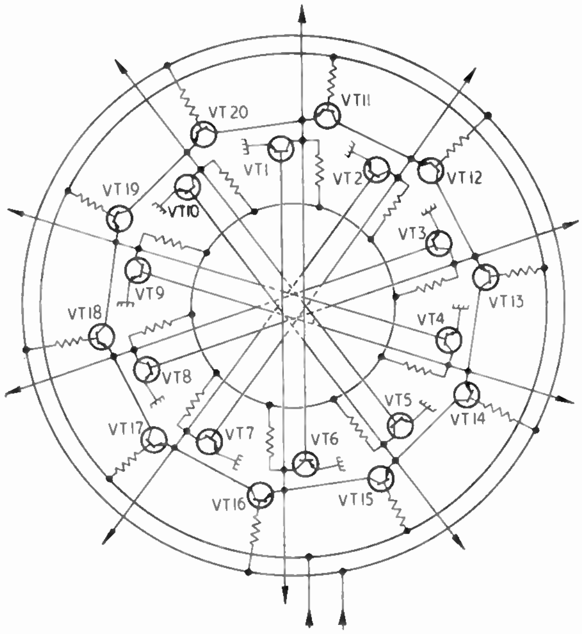


Fig. 9. Decade ring counter.

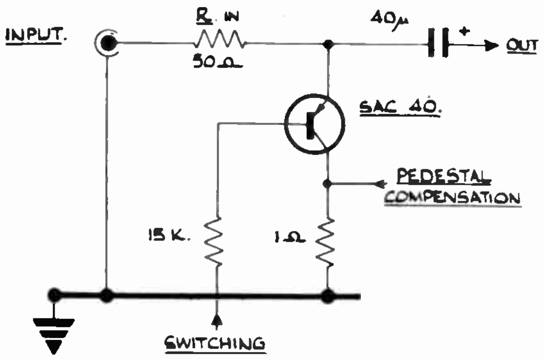


Fig. 10. D.c. chopper.

The whole subject of transistor choppers has been very well covered by recent papers. A typical circuit is shown in Fig. 10.

3.3. *Symmetrical Transistors*

Another approach to the problem of converting small, slowly changing signals into modulated a.c. is to use a balanced modulator technique.† Here the requirement is for a pair of back-to-back silicon diodes with matched forward impedance. A symmetrical silicon transistor made by the process described meets this requirement, with the added advantage that a physical separation between the diodes of only 0·0003 in. of silicon web maintains a close match of diode characteristics over a wide temperature range.

3.4. *Video Amplifiers*

Finally, the high frequency performance and linearity of this type of transistor make it very suitable for video amplifier applications where, in a high ambient temperature, a moderate voltage gain is required to give an output of a few volts over bandwidths up to 4 Mc/s.

4. Acknowledgment

The author gratefully acknowledges the permission of the Directors of Semiconductors Limited to publish the technical information presented in this paper.

Manuscript received 15th August 1960 (Paper No. 614).

† J. Evans, D. A. Gill and B. R. Moffitt, "Symmetrical transistors as a.c. or d.c. switches and their applications in modulator and demodulator circuits", *J. Brit.I.R.E.*, **21**, pp. 143–9, February 1961.

Electronic Signal Interlocking for British Railways

As part of the railway modernization programme, the British Transport Commission has awarded a contract to Mullard Equipment Limited for the development of an electronic signal interlocking plant. The equipment will be the first plant using electronic interlocking to be used on British Railways and will replace the mechanical interlocking on the lever frame at Henley-on-Thames Western Region signal box. It will be installed during the early summer of 1961.

Recently the Company was able to demonstrate to British Railways' signal engineers and to a representative of the Institution a working model of a double junction, completely controlled by the new electronic system. The technique has the substantial advantage that it employs solid-state electronic circuitry throughout resulting in a system which eliminates the use of moving parts, thus greatly reducing long-term maintenance costs. A further advantage is that the new development could reduce the size of the installation itself and of the building required to house it, while economies in the storage of replacement parts is made possible. Adoption of electronic interlocking for future signalling schemes will depend largely upon its ability to surpass the outstanding reliability of magnetic relays, which can operate for a minimum of five years in a sealed box and have a failure rate of only one in thousands of millions of operations.

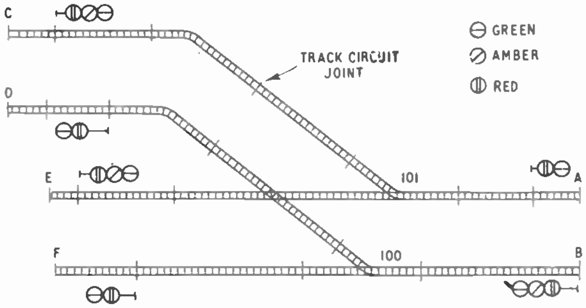


Fig. 1.

The model works on the conventional "entrance-exit switch and push button" system, and track and point indication is provided. The only relays used are track relays and for convenience in the demonstration, these are of the Post Office type. In order to set up a route on the model, for instance, in the direction B to D (see Fig. 1), the direction switch at B is set to direction B to F and the exit button at D is pressed. This action results in the points 100 and 101 being moved to the reverse position. These points are interlocked and the sequence is that 101 is reversed first and when it has been detected as being reversed, the points 100 are reversed. However, this route B to D can only be called provided that the information from the track circuits involved indicates that there is no vehicle on the track and also that the points are not locked—that is to say, that a prior route has not been set up along, for instance E to A.

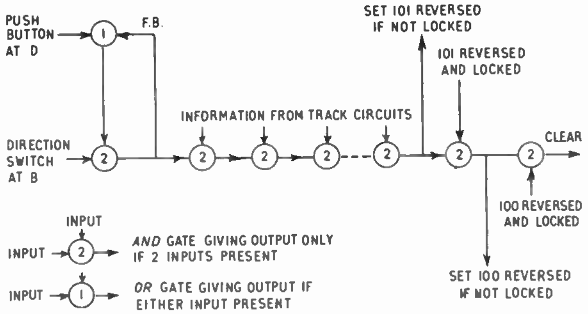


Fig. 2.

A simplified example of a sequence of events is shown in Fig. 2. The pulses from the push-button at D is fed to an OR gate which sets up a feedback path to maintain the circuit. The output from the OR gate is fed, together with the signal from the switch at B, to the AND gate which then—and only then—gives an output to the first track circuit AND gate. This input together with the input from the track circuit (providing this is clear) will result in an output to the next track circuit AND gate and so on. After all the track circuits have given the information that they are unoccupied, the points 101 are reversed, providing they are not locked, and the signal from the track circuits together with the information that 101 is now reversed and locked is fed to another AND gate. The points 100 are now reversed and locked, and this information, together with the output from the last AND gate, is fed to the final AND gate, the output of which clears the signal at B (see Fig. 1).

This is a logical process and if for any reason the required information does not reach any one of the AND gates in the chain the sequence will be broken and the route will not be cleared. When a route has been cleared and a train travelling in the direction B to D, for example, has passed over the first track circuit in the route, the signal is automatically returned to red. Although the direction switch is still set, this route cannot be used again, by pressing the exit button, until the whole sequence of calling has been repeated.

In addition to the interlocking of the points and the use of track circuits, there is also a device whereby if a signalman has set up a wrong route (B to F instead of B to D for instance) he is unable to reset the route immediately if a train has already entered the approach track circuits. He can however set all the signals to red, and after a suitable time delay to allow the train to stop the route can be reset. Obviously if this device were not included a signalman would be able to reverse the 100 points, which may not complete their movement before the train reached them and thus cause a derailment.

The logic system can therefore provide an anti-preselection device and an approach locking device to meet signalling requirements, and has the advantage that track circuits of the normal type are used. While present equipment has been designed to meet the requirements of British Railways, it is generally applicable to railway systems anywhere in the world.

The electronic logic units from which the system is constructed are of the plug-in type and there are four basic units. They are designed to operate safely in ambient temperatures between −20° C and +50° C. They employ transistors, semiconductor diodes and ferrite cores. Circuit techniques different from those employed for logic units used in ordinary industrial equipment have been required in order that a unit should always "fail safe": i.e., any failure will switch appropriate signals to "red".

Although electronic signal interlocking will not be featured at the forthcoming Electrical Engineers Exhibition in London, communications and signals generally will have particular prominence. British Railways are intending to show, both by means of models and actual equipment, many of the recent developments in the electrical engineering aspects of railway modernization. The exhibit will include a model, specially prepared for the exhibition, of the latest overhead equipment, with actual signal-cabin controls installed to operate signalling and track-side electrical equipment, the cabin being built alongside a station platform complete with standard track. The railways exhibit will not only be a display of present work, but will also give emphasis to research programmes on signalling relays, recorders for movement information, controlling equipment for electrical power supply, and many other features concerning communications.

An Electronic Reading Machine for Computer Input

Members who attended the Institution's 1957 Convention on "Electronics in Automation" will recall that one of the most interesting contributions was "Automatic Reading of Typed or Printed Characters" by Mr. C. E. G. Bailey and Mr. G. O. Norrie. At that time it was only possible for the authors to describe the principles of operation and construction of a prototype machine, which was in fact not complete in all the facilities which it was realized it would require. Recently after a period of intensive development, the authors' company, The Solartron Electronic Group, have announced the completion of the first production model of the ERA, or Electronic Reading Automaton.

This equipment will read printed characters accurately at a very high speed by means of a cathode-ray tube. This produces a light spot which traces on the tube face a raster of 15 lines; a lens projects an image of the raster on to the character, and the reflected light is picked up by a photo-multiplier cell. Thereafter the electrical signal, which will vary along each of the lines according to whether the image picked up is black or white, i.e. part of the character being read or not, is roughly similar to a television video signal. It is cleaned up by eliminating any spurious responses and then fed to logical circuits which produce output signals in binary or other code suitable for operating card or tape punches, or magnetic tape units, or for feeding to a computer.

The machine is designed to read either continuous rolls of paper or separate documents—the present first production model is intended for use with cash register rolls, and for this purpose Solartron have collaborated with the customer and manufacturers of the cash registers used to evolve a suitable type face for the digits 0–9, and 10d., 11d., and ½d., plus or minus signs, and a few letters of the alphabet. It is claimed that the speed of operation of translating printed information into the appropriate machine language can be as high as 300 characters per second.

Discussing the reasons for adopting optical rather than magnetic character recognition, Mr. Bowman Scott, Managing Director of Solartron Electronic Business Machines Ltd., told an Institution representative that the optical system gave higher resolution and could therefore sense and use more of the information available on the paper. One of the prices paid for this higher resolution is a larger number of logical circuits, but the system does allow a lower print quality, a point of considerable advantage where a large number of outstation printers are in use. It is also unnecessary to seek a highly specialized type fount, and obviously special inks are not required.

Radio Engineering Overseas . . .

The following abstracts are taken from Commonwealth, European and Asian journals received by the Institution's Library. Abstracts of papers published in American journals are not included because they are available in many other publications. Members who wish to consult any of the papers quoted should apply to the Librarian, giving full bibliographical details, i.e. title, author, journal and date, of the paper required. All papers are in the language of the country of origin of the journal unless otherwise stated. Translations cannot be supplied. Information on translating services will be found in the Institution publication "Library Services and Technical Information".

V.H.F. QUARTZ CRYSTALS

The highest frequency of v.h.f. crystal units in practical use produced by lapping is considered to be about 75 Mc/s, and this limit seems to be caused by vibration loss due to irregularities of the surface quartz. Investigations have been carried by the Japanese Telegraph and Telephone Public Corporation into polishing techniques used for finishing the surface. It is stated that, with attention to the working methods, processes and precise measurements of the mechanical properties of quartz plates, it should be possible to establish a technique for making crystals with frequencies of up to 140 Mc/s and to obtain a reasonable yield. The paper describing the work discusses the phenomena of deformation of thin polished plates, the nature of skin stress, and the depths of mechanical disturbance. With the results thus obtained, the mechanism of polishing quartz is explained as the aggregation of micro-scratchings by points of abrasives. Further, a model of the polished layer, by which mechanical factors having influence on the vibration loss may be suggested, is shown.

"V.h.f. crystal polishing and the nature of polished quartz surfaces", I. Ida and Y. Arai. *Review of the Electrical Communication Laboratory, N.T.T.*, **8**, Nos. 3–4, pp. 119–174, March-April 1960. (In English.)

D.C. AMPLIFIERS

Sensitive d.c. amplifiers call for elimination of drift and a recent German paper puts forward a circuit providing drift compensation. This is a push-pull amplifier stage with two valves having a common high resistance in the cathode lead. On a potentiometer connected between the anode of the valve and the common cathode a potential point can be established that remains independent of in-phase controlling effects on the two push-pull valves (such as drift disturbance, mains voltage variations, hum pickup, etc.), while with out-of-phase control the useful signal appearing at the anodes in an amplified form is reduced only by the voltage dividing factor of the potentiometer setting. Finally an amplifier is described where virtually no drift disturbance could be measured with an equivalent in input noise voltage of about 70 μV (bandwidth 0 to 11 c/s).

"D.c. signal amplifier with reference to stability of zero", *Archiv der Elektrischen Ubertragung*, **14**, pp. 543–46, Dec. 1960.

FAST SCANNING RADAR AERIAL

The construction of a fast-scanning radar antenna based on Rinehart's analogue of a two-dimensional Luneburg lens is described in a recent Dutch paper. The antenna consists of two hat-shaped metal plates, which together constitute a waveguide and which convert the circular wave fronts in a given plane from a point source on the circumference into linear wave fronts. All that revolves is a rectangular waveguide, the mouth of which acts as the point source. This makes it readily possible to achieve a scanning speed of 10 rev/s, which is necessary when fast-moving objects are to be followed clearly or when a bright radar pattern is required. An experimental radar antenna of this type for a wavelength of 1·25 cm has an average 3 dB beam width of 1·5 deg in the horizontal plane and of about 25 deg in the vertical plane. A 200 W motor is sufficient for the drive.

"A high-speed scanning radar antenna", F. Valster. *Philips Technical Review*, **22**, No. 2, pp. 29–35, 1960–61. (In English.)

SURFACE WAVE TRANSMISSION LINES

A Hungarian paper has recently dealt with investigations of surface-wave transmission lines, with the main object of determining their losses. A new procedure was worked out to measure the attenuation factor directly, and the standing-wave-ratio and the bandwidth of surface-wave transmission lines and the electric field distribution around the conductor determined. The attenuation factor varied from 0·02 to 0·2 dB/m dependent on frequency, conductor material and coating. The launching loss was found to be between 1 and 4 dB, dependent on horn sizes and frequency. The standing-wave-ratio of the transmission lines remained below 1·3 in a very broad band. The width of this band was between 600 and 900 Mc/s for different lines. A measurement of the field distribution around the wire showed that field-concentration becomes more effective with increasing frequency. Numerous experiments performed on different transmission lines yielded results in agreement with theoretical predictions relating to dependence on frequency and other parameters.

"Investigations on surface wave transmission lines", T. Berceli. *Acta Technica (Budapest)*, **25**, No. 3–4, pp. 257–74, 1959. (In English.)

TRANSISTORS FOR TELEPHONE SWITCHING

Work carried out in the Electrical Communications Laboratory of the Japanese Telegraph and Telephone Public Corporation on bilateral speech path switches for all-electronic telephone exchange systems has recently been described. The main object of this research was to obtain elementary semi-conductor speech-path circuits which can be connected with each other directly, without using coupling circuits such as transformers or capacitors between stages. This feature is desirable for multi-stage connection in a large scale exchange system. The first circuit uses a diode bridge, the second circuit uses grounded base *pnp* and *npn* transistors connected alternately, and the third circuit uses a compound *pnpn* transistor made up of one *npn* transistor and one *pnp* transistor. For practical use, the last circuit seems to be the most promising and a further paper examines these hook connections for suitability for applications as speech-path switches in space-division exchange systems. The static characteristics and the switching speeds are first considered from the equivalent circuit of the compound transistors for the case of a three-terminal configuration. The automatic lock-out functions and the properties of the multi-stage cascade connections, which may be available for end marking systems of speech-path networks, are considered. Furthermore, some properties of two terminal configurations are also described.

"Semiconductor speech-path switches suitable for direct-coupled connection", I. Endo and S. Yoshida, and "Properties of compound transistors for speech-path switches", I. Endo, K. Yamagishi, S. Yoshida and K. Goto. *Review of the Electrical Communication Laboratory, N.T.T.*, **8**, Nos. 3–4, 5–6, pp. 105–111, 211–221, March-April, May-June, 1960. (In English.)

ELECTRONIC REVERSAL OF COLOUR NEGATIVES

To investigate the possibilities of electronic reversal of colour negatives, a flying spot scanner with three input channels and a reproducing device has been developed at the Institute for High-frequency Technique in Berlin. The distortion of brightness and colour introduced by the film and the system is reduced by gamma-correcting and masking stages. The coefficients of the masking matrix are found from well-known test colours on the one hand and their photographic negative renditions on the other. The usefulness of the system is determined by a comparison of original colours and their rendition. With nine test colours distributed over the spectrum the mean spacing on the rectangular uniform chromaticity scale is $d = 9{\cdot}8 \times 10^{-3}$, with the maximum deviation found in the blue region. Upon suitable calibration of the correcting elements, the system can be used as a simple film analyser.

"Electronic reversal of photographic colour negatives", K. Welland. *Archiv der Elektrischen Ubertragung*, **14**, pp. 441–50, October 1960.

DISTORTION IN TRANSISTOR RECEIVERS

Considerable cross modulation and modulation distortion are often experienced in a.m. receivers employing transistors. A Dutch paper examines the causes of these phenomena and investigates to what extent and under what conditions they are introduced by the transistor itself and the h.f. amplifier stages. Indications are also given of the steps to be taken in designing these stages so that cross modulation and modulation distortion are kept within acceptable limits. The agreement between the theoretical analyses and experimental results appears to be remarkably good, notwithstanding the simplifications introduced for deriving the formulae.

"Cross modulation and modulation distortion in a.m. receivers equipped with transistors", A. H. J. Nieveen van Dijkum and J. J. Sips. *Electronics Applications (Eindhoven)*, **20**, No. 3, pp. 107–28, 1960. (In English).

TRANSIT TIME EFFECTS IN HIGH POWER VALVES

For frequencies up to 800 Mc/s the operational behaviour of high-power transmitting tetrodes can be stated with good approximation on the basis of a calculation of the transit-time effects. A recent German paper explains the fundamentals of this calculation which is based on a purely graphical method. For the case of television operation at 800 Mc/s and black-level modulation, the operational behaviour of the 10-kW transmitting tetrode RS 1032C is illustrated by reference to graphs. Finally some general problems are discussed such as the optimum design of electrode spacings, the heating of the cathode by electron bombardment and the phase modulation in the output circuit.

"Electron transit time effects in transmitting tetrodes for the television bands IV/V", W. Seiffarth. *Archiv der Elektrischen Ubertragung*, **14**, pp. 491–98, November 1960.

RECORDING TELEVISION SIGNALS

A description of a magnetic wheel store for recording single television frames is given in a Dutch publication. It is stated that good results are achieved by frequency-modulating a carrier with the video signal. The frequency range of the recording is approximately from 0·5 Mc/s to 8 Mc/s. The minimum wavelength on the wheel is 8 μm at 8 Mc/s. A device is described whereby the write-read head rides on an air cushion at a distance of about 1 μm from the magnetic rim of the wheel. Also discussed are a circuit for writing and reading a single frame and a system of synchronizing the wheel with the video signal. A promising application mentioned is the recording of X-ray images.

"A magnetic wheel store for recording television signals", J. H. Wessels. *Philips Technical Review*, **22**, No. 1, pp. 1–10, 1960. (In English).