The Journal of
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" To promote the advancement of radio, electronics and kindred subjects by the exchange of information in these branches of engineering."

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VOLUNTARY SERVICE

IT is often said that Annual Reports, whether of a corporation or a company, are seldom read, provided that the appended Accounts are satisfactory. Whilst we may hope that the same does not apply to the Annual Reports of Institutions, it is a fact that only a small percentage of members attend the Institution's Annual General Meetings.

On the other hand, unsatisfactory Accounts, whether of a company, corporation, or Institutions, invariably attract a very large attendance at the Annual General Meeting. This quirk of human nature is easily explained: if all is well there is no need to have an enquiry!

Apathy, in its application to Institutions or, indeed, any voluntary organization, implies a negligence to recognize the appreciation due to those whose work has resulted in a modicum of success. All enterprises in social service stem from people who, without thought of personal reward, possess the desire to render service either to a well-deserving cause or to their fellows. It is the purpose of these notes to acknowledge such service.*

Expression of voluntary service may take many forms; some individuals are better fitted for charitable endeavour, others for the promotion of public well-being, in which category we may place those who aspire to political achievement. From all sections of the community, however, there are many who desire to work in their own professional sphere.

Such are the members who give voluntary service to the Institution and who endeavour to reflect the feelings of the entire membership on matters which come within the purview of a professional body. Some members have a particular interest in ensuring that adequate educational facilities are available in order to provide the younger generation with opportunity to achieve success in their engineering career. Other members are especially concerned to secure wider dissemination of technical knowledge and exchange of technical opinion. Assessment of membership eligibility and ability to frame policy also call for experienced help.

Indeed, the titles of Standing Committees in all Institutions show a very wide range of topics; finance, administration, printing, and personal service, such as a Benevolent Fund, all call for the help and advice of a large number of members. To secure the best opinion involves the co-operation of members with a keen interest in a particular subject, coupled with a willingness to devote a considerable amount of time as well as ability.

In Great Britain, the contribution of voluntary effort towards serving a worth while cause is recognized in several ways; the most important recognition which can be given to a charitable body, a corporation, or an Institution is the granting of a Royal Charter. The achievement of such a distinction would not be possible without the help of those who consider it worth while to give voluntary service.

Thus, the Annual Report of the Institution is much more than a legal formality; it is an account of the work of those who voluntarily undertake the task of acting as trustees for the membership as a whole in one or other of the specialized aspects of the Institution's work; it is also an expression of thanks on behalf of the entire membership to those who have made it possible to publish such a Report.

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* See also *J.Brit.I.R.E.*, **6**, page 81, June 1946, also entitled "Voluntary Service."

THE WORK OF STANDING COMMITTEES

The Annual Report gave an overall view of Institution activities during the past year. These notes provide a background to the work undertaken by the various Standing Committees.

EDUCATION AND EXAMINATIONS

ONE of the most important activities of the Institution lies in the field of technical education. During the past year the Institution's Graduateship Examination has broadened in scope and the first examination based on the new syllabus was held in November, 1956. This has involved the Committee in much additional work, details of which were given in the Annual Report.

Changes in the syllabus call for close co-operation with all the major educational establishments in Great Britain, throughout the Commonwealth, and in other countries from which candidates are likely to enter. Thus, details of the revised syllabus were circulated to technical colleges, etc., some two years before the new examination scheme came into force.

It is, of course, the policy of the Council to give every possible help to teaching establishments, especially where opinion and perhaps assistance is required in framing syllabuses not only to cover the Institution's but other examinations best suited to the industrial requirements of a locality, and the desire of students wishing to take various examinations.

Thus, in stimulating interest in technical education, the Institution aims to help students to equip themselves with the necessary ability to qualify as professional engineers. To that end, it is necessary to visualize a scheme of education and training which will best enable students, after suitable experience, to assume responsibility in engineering development or perhaps even research, design or manufacturing/production engineering.

In the course of such work, he will normally be required to accept responsibility for technicians working under his guidance, and it is appropriate, therefore, that through his professional body the engineer should give assistance in the proper training of technicians. It is for this reason that the Institution continues to be represented not only on the City and Guilds of London Institute Advisory Committee on Telecommunications Engineering, but also on the City and Guilds of London Institute Advisory Committee for Radio Service Work and on the Radio Trades Examination Board.

The pioneer work of the City and Guilds of London Institute in encouraging the study of Radio Engineering and Telecomunications has always been acknowledged by the Institution. Notwithstanding the changes which have taken place in the Higher National Certificate scheme, the City and Guilds of London Institute continues to attract a very large number of candidates for the Telecommunications Engineering Examinations. No less than 39,000 candidates entered for these examinations during 1956—a considerable proportion of the total number of 112,000 examinees which the City and Guilds of London Institute had for the 201 examinations which it holds.

In the broad group of Radio and Telecommunications Engineering Examinations, however, it is disappointing to note that only 90 candidates succeeded in obtaining Full Technological Certificates in Telecommunications Engineering during 1956. The scheme is therefore being re-examined by the Advisory Committee on Telecommunications Engineering, on which the Institution is represented.

A further development in higher technological education is the new award known as the Diploma in Technology. Eighteen courses, seven of which specialize in radio and electronics, have already been recognized by the National Council for Technological Awards as leading to the Diploma in Technology.* It is too early to see the effect of this new scheme, which aims to supplement the number of University Graduates. It is apparent, however, that a number of colleges are anxious to offer specialist courses in the radio and electronics field, which ultimately should be to the advantage of the profession and industry.

Common Preliminary Examination.—During 1956, the Institution sponsored 51 entries for the Common Preliminary Examination; un-

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* *J.Brit.I.R.E.*, **17**, p. 210, April 1957; p. 430, August 1957.

fortunately only seven of those candidates were successful.

As stated in the report of the Membership Committee, insistence on success in the Examination, or the possession of exempting qualifications recognized by the Engineering Joint Examinations Board, has resulted in a decrease in the number of Students registered with the Institution during the year. Representations are frequently made for some easing of these requirements, but the Council has reaffirmed its opinion that unless students are able to meet the requirements of the Common Preliminary Examination, it is most unlikely that they will succeed in their subsequent studies for either the Institution's Graduateship Examination or the Higher National Certificate, with appropriate endorsements.

The overall results reported by the Engineering Joint Examinations Board are of the greatest significance to teachers and to all responsible for education up to Grammar School standard.

Acknowledgments.—Very many members have served the Institution by acting as assessors, representing the Institution on Visiting Committees and, in particular, undertaking the responsibility of examiners. In this latter connection, the Council especially records appreciation of the work of the following members who have done much to maintain the standard of the Institution's Graduateship Examination by acting as examiners:—

E. W. Pulsford, B.Sc. (Chairman).
D. A. Crowther, B.Sc.(Eng.).
K. W. Cunningham, B.Sc.
K. E. Everett, M.Sc.
D. Fotheringham, B.Sc.
J. A. Hutton, B.Sc.
K. R. McLachlan.
W. J. Perkins.
Sqd. Ldr. W. L. Price, M.Sc.
E. T. A. Rapson, M.Sc.
H. V. Sims.
F. M. Walker, B.Sc.
E. M. Wareham.
P. O. Wymer, B.Sc.

Many Universities and Technical Colleges throughout the world are now used by the Institution as regular centres for the Graduateship Examination. Considerable assistance has also been given by various Service establishments and the British Council in providing accommodation for candidates not having reasonable access to regular examination centres. Council expresses thanks to the many authorities concerned for the facilities and accommodation provided.

Radio Trades Examination Board.—The Council has been pleased to continue the Institution's association with the Radio Trades Examination Board. Older members will know that the idea of trade or craft examinations in radio was originated by the Institution in order to give professional help and encouragement to the training of mechanics and craftsmen.

From the inception of the scheme in 1942, the Institution, the Radio Industry Council, the Scottish Radio Retailers' Association, and the Radio and Television Retailers' Association have jointly financed the Board's operation.

How well the scheme has been justified is evidenced by the fact that over 5,500 candidates have submitted themselves for the Radio and Television Servicing examinations—a most useful contribution toward fulfilling the Board's principal object—"*the promotion of a high standard of skill and efficiency of persons employed as radio mechanics, technicians and tradesmen.*"

In view of the active work of the Institution in the formation and operation of the Board, the Annual Report of the Board—the first since incorporation—was published in a recent issue of the Institution's *Journal.**

During 1956, 822 candidates entered for the Radio Servicing examination, and 138 for the Television Servicing examination. These were the highest figures ever recorded, and the entries for the 1957 examination show an even greater increase—1,140 for the Radio Servicing examination and 247 for the Television Servicing examination.

An intrinsic part of both examinations is the practical test. The combined figures for 1956 and 1957 show that out of 1,962 candidates entering for the Radio Servicing examination, 610 failed completely, whilst another 521 failed in the practical examination. The figures for the Television Servicing examination indicate that of the 385 examinees, 106 failed entirely, and a further 99 candidates failed the practical examination, although, in accordance with the

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* *J.Brit.I.R.E.*, 17, p. 235, April 1957.

regulations, all candidates had previously satisfied both sections of the Radio Servicing examination.

There has, however, been some improvement in results as compared with earlier years, and evidence that an increasing number of candidates are indentured apprentices and/or attending part-time day release courses at technical colleges. It is interesting to note that, as with course work in preparation for the professional examinations, there is a proved need for devoting more time to laboratory and practical work.

The standards set are such as will commend successful candidates to employers both in the radio industry and trade. It has, therefore, been necessary for the Board to set up an appointments service to meet enquiries made by employers and by holders of the Board's Certificates.

The Institution is represented on the Council of Management by three members, and other members of the Institution serve on the Board's Education and Examinations Committee. In addition, the Institution continues to provide secretarial facilities.

It is a matter of great regret to the Institution that the death of Mr. E. J. Emery (Member) deprived the Board of the services of its second Chairman.* Mr. Emery was one of the representatives of the Radio Industry Council and had been a member of the Board since it was formed in 1941.

Future Work.—The Education and Examinations Committee has always been one of the most active Committees in the Institution and under its aegis a most useful wall chart has been prepared on "Careers in radio and electronic engineering." Work has also begun on a special report on careers and technical education in the whole field of electronic engineering, which should prove most valuable to all who are interested in technical training and recruitment to the engineering profession as a whole.

PROGRAMME AND PAPERS COMMITTEE

The Journal.—As stated in the Annual Report, papers published in the *Journal* during 1956 have covered an extensive range of subjects within the wide field of radio and electronic engineering.

The principal concern of the Committee is, of course, the selection of papers of a high standard for publication in the *Journal*. One measure of the past year's success in this direction is the increase in the number of pages of the 1956 bound volume to a record level of 700.

During 1956-7 the number of papers considered for publication in the *Journal* was 57, excluding Convention papers: 59 per cent. were suitable compared with 42 per cent. of those submitted during the previous year, and 10 per cent. were acceptable after revision.

The Council takes this opportunity of thanking the members of the Committee for their work in the selection of papers, and the many other members who have reported on the suitability of manuscripts for publication in the *Journal*.

The policy of including in the *Journal* articles of general interest to the radio and electronics engineer has been continued, and such articles have covered a wide field, ranging from television transmitting stations to the utilization of atomic energy. The feature "Radio Engineering Overseas" which gives abstracts of selected papers from European and Commonwealth Journals continues to be a useful service to members and notices of exhibitions and similar events have been appreciated.

Guidance for Authors.—The Committee is continually concerned with helping authors to present manuscripts in a form suitable for publication. Recommendations on the revision of a paper often require the author to improve the general style and presentation, a matter which, in some cases, involves the complete re-writing of the paper. With a view to helping authors to draft their manuscripts in more suitable style from the beginning, the Committee prepared an article entitled "Guidance for Authors of *Journal* Papers," which was published in the *Journal* (June 1957), and which is also available in leaflet form. Practical advice

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* *J.Brit.I.R.E.*, 17, p. 254, May 1957.

is given on style and presentation and on the layout of a manuscript, while some brief notes are included on the preparation of illustrations and on the oral presentation of papers at meetings. The Committee hopes that this leaflet will be useful to all authors and particularly to those who are making their first attempt at writing for a professional journal.

Meetings.—Eleven meetings were held in London during the 1956-57 Session, including one discussion meeting and one meeting at which films of historic and general interest on valve manufacture were shown. Whilst the average attendance has been 120, some meetings attracted a near capacity audience. In order, therefore, that members of the Institution can be assured of accommodation, the number of visitors has had to be limited by requiring that they should obtain tickets in advance through members.

The Local Sections based in Scotland, the North East, the North West, Merseyside, the South Midlands, the West Midlands and South Wales have all held regular meetings during the session. Although the imposition of petrol rationing at the end of 1956 reduced attendances at meetings, particularly in the case of those Sections having a widely dispersed membership, 46 meetings were held by the seven sections. The Council was pleased to note the progress made by the new South Midlands Section which was inaugurated in October 1956.

The Overseas Sections, in India, New Zealand, Pakistan and South Africa have held meetings during the year. As has been recorded in previous years, the opportunities for local sections overseas to arrange full programmes are necessarily rather limited, but the local Committees have devoted themselves very conscientiously to this problem.

Co-operation with the I.R.E. Australia.—Members will be aware that, in alternate years, the Institution and the American Institute of Radio Engineers make recommendations for the award of the principal prize of the Institution of Radio Engineers, Australia.

During 1956 the Brit.I.R.E. recommended that this award—the Norman W. V. Hayes Memorial Medal—should be given to J. Swift for his paper on "Disc-Seal Circuit Techniques." It will be recalled that two parts of this three-part paper were reprinted in the *Brit.I.R.E. Journal* for December 1955 and February 1956. The Council continues to value the co-operation between the two Institutions, of which this mutual agreement for re-printing papers is but one aspect.

Extension of Interests.—The aim of the Committee must always be to achieve a balanced selection of papers for the *Journal* during the year: the procurement of papers in the final analysis depends on knowing about work in progress in the different branches of radio and electronic engineering. Consideration is therefore being given to the setting up of several informal groups of members connected with the various branches who would be primarily concerned with obtaining papers for publication from within their spheres of interest. It is hoped to report more fully on this scheme in the next Annual Report.

LIBRARY COMMITTEE

The Technical Committee is now co-operating with the Library Committee in the preparation of a reference book of Library Services and Technical Information for the radio and electronics engineer. This publication will include lists of lending library and reference books under a U.D.C. and author index, reference data on the British Standards Institution and its publications, other engineering standards, abstracting organizations, etc. It is hoped to publish this reference work by the end of 1958, and copies will be circulated to all members.

The work of the Library is expanding, as evidenced by the fact that 1,062 books were borrowed by members during the year. Reference services have also been made available to a number of companies.

Additions have brought the stock of the lending and reference works to over 2,000 volumes. This is in addition to bound volumes of selected periodicals, of which 136 are now regularly received either by paid subscription or by reason of exchange with the Institution's *Journal*.

The accommodation problem of the library has been helped by further increasing the shelving space. The library is now equipped throughout with 12 ft. high shelving; even so, it is difficult to see how the limited facilities of the present building can accommodate the normal expansion of the library if the reference service is to be maintained.

By using accommodation in other parts of 9, Bedford Square, it should now be possible to absorb some four or five years' normal intake of books into the main Library. Thereafter, the Committee is hopeful that the Institution will have acquired new premises providing larger library accommodation in order that the efficiency of this service may be maintained.

As well as the reorganization of accommodation, a new lending record system has been adopted, the chief aim of which is to minimize the time spent in locating a book which is on loan. This system has provided interesting statistics on members who use the Library. For example, students are the main users of the Library during the two or three months before examinations, but over the year, the number of student users is only a third of that of members of other grades!

All requests from members for books, periodicals and other references, such as house journals, were met. This has been partly achieved by co-operation with other libraries, both industrial and public, through which the Institution has had access to a wide range of material not otherwise obtainable. The Committee particularly wishes to express its appreciation to the librarians of the organizations concerned for their assistance.

The librarian continues to obtain photocopies of periodicals, etc., from the Science Library for members wishing to retain copies of articles—a service which is especially appreciated when a periodical is out of print.

Acknowledgments.—The Committee expresses thanks to all those who assist the Library in many ways. In particular, they wish to record thanks to Mr. W. R. Dedman (Graduate), and Mr. W. C. Green (Associate Member) for their most welcome donations to

Members serving on Committees of the British Standards Institution

(The Institution is represented on all the main Technical Committees of the Telecommunications Industry Standards Committee. In addition representatives are appointed on other Industry Standards Committees where the work has a bearing on Radio Engineering.)

TLE/1 Terminology and Symbols for Telecommunications
F. G. Diver, M.B.E. (Member)

TLE/1/1 Nomenclature and Letter Symbols for Telecommunications
Group Captain S. G. Morgan (Associate Member)

TLE/1/2 Graphical Symbols for Telecommunications
To be appointed

TLE/2 Radio (including Television Receivers)
F. T. Lett (Associate Member)

TLE/3 Radio (including Television) Transmitters
J. R. Brinkley (Member)

TLE/4 Components for Telecommunications Equipment
M. H. Evans (Associate Member)

TLE/5 Electronic Tubes
G. R. Jessop (Associate Member)

TLE/8 Measuring Instruments and Test Equipment
E. D. Hart, M.A. (Associate Member)

TLE/9 Aircraft Radio Equipment
S. J. H. Stevens, B.Sc.(Eng.) (Associate Member)

TLE/11 Piezo-Electric Crystals
S. Kelly (Member)

TLE/12 Transistors
B. R. A. Bettridge (Associate Member)

ELE/32 Radio Interference
O. E. Trivett (Member)

ELE/66 R.F. Heating Equipment
R. E. Bazin (Member)

ACM/8 Electro-Acoustic Transducers
H. J. Leak (Member)

the Library in the form of books and periodicals, and to the many publishers who supply new technical books for review and subsequent inclusion in the Library.

TECHNICAL COMMITTEE

Reports.—The main concern of the Committee during the early part of the year was the continuation of the series of reports on "Materials used in Radio and Electronic Engineering." Part 4—Plastics, and Part 5—Electrodeposition of Metals, were published in the *Journal* during the year. Both these reports were extremely well received, and in view of the demand for these and earlier reports, it has been agreed by Council that the first six in the series should be collected and published together as a booklet.

Mention was made in the last Annual Report of the presentation of characteristics of electronic instruments, when it was stated that there is no standard method of presenting this information. The Committee has therefore in hand a new series of publications under the general heading "Methods of Expressing the Characteristics of Electronic Instruments."

The first of the series "Amplitude Modulated and Frequency Modulated Signal Generators" is now ready for publication, and should be particularly valuable for engineers concerned with the use of high grade instruments. In this connection the Committee has been greatly assisted by the work of the Radio and Electronic Measurements Committee of the Ministry of Supply, who are working in a similar field. With the agreement of that Committee, it has been decided to standardize the expressions and terms used, and to include a number of new definitions.

Arbitration.—Many requests have been received for the services of members of the Institution to act as impartial technical assessors in cases of arbitration, as consultant engineers and as technical witnesses.

The Technical Committee has been able in all cases to appoint appropriate members of the Institution or to give technical advice.

Standards.—The Committee has maintained close liaison with representatives of the Institution who serve on the various technical committees of the British Standards Institution. The need for greater international co-operation on standards amongst the West European countries forming the proposed Free Trade Area is very apparent, and the Committee is studying this problem to determine what assistance can be provided by the Institution.

FINANCE AND THE FUTURE

How best to counter rising costs has dominated the discussions of the Finance Committee. Printing, paper, and postage costs together account for more than one third of total Institution expenditure. All these items have increased during the past year, and will show an even greater increase in the current year. For example, in 1956 the cost of newsprint was increased by £3 10s. 0d. per ton, and by a further £1 per ton at the beginning of 1957. Higher quality paper, of which some 18 tons is used for the *Journal* during twelve months, had a corresponding increase, and although advertising has provided more revenue, it has not wholly offset the cost of paper increases.

Other publications of the Institution which do not carry advertising have had to be re-designed in order to offset this cost. Similarly, printing costs have increased as a result of two wage increases in the last three years in the printing industry. Current indications are that paper costs may become lower as a result of increased competition in this field, but any saving is likely to be offset by a further increase in printing charges.

These are only some of the problems of the Finance Committee. A partial solution is provided by the continual growth in membership, whilst increasing appreciation of the *Journal* and its influential circulation makes it more attractive to advertisers.

Future expansion of Institution services calls for a form of capital investment. Undoubtedly the whole financial structure of the Institution will be more firmly based when a more suitable building has been acquired. In this connection, much encouragement is derived from the widespread support being given to the Building Appeal, and from the generous contributions of an increasing number of manufacturers which in effect provide the Institution with working capital.

INSTITUTION NOTICES

OBITUARY

The Council has learned with regret of the death, on November 6th, of John Kenneth Barker (Graduate).

Mr. Barker was with the Flight Simulator Division of Redifon Ltd., Crawley, and had been with the Company for four years. He was project leader in charge of the development of the flight simulator for the Bristol "Britannia" and met his death when a "Britannia" crashed during trials.

Elected a Graduate of the Institution in 1949, Mr. Barker was 34 years of age. He leaves a widow and two children.

Dinner of the Scottish Section

The Annual Dinner of the Scottish Section will be held on Friday, January 31st next, at the St. Enoch Hotel, Glasgow.

The President of the Institution will be attending and one of the speakers will be Major-General S. W. Joslin, C.B., C.B.E., M.A., Works General Manager at the Dounreay establishment of the U.K. Atomic Energy Authority.

Tickets may be obtained from the local Honorary Secretary of the Section, Mr. J. B. Rimmer, 5 Cromarty Avenue, Newlands, Glasgow S.3.

"Talking Books" for the Blind

Many blind people have received, through the Nuffield Talking Book Library for the Blind, portable mains or battery operated gramophones for playing recordings of books. Although the equipment is relatively simple, it may present difficulties to the blind user. The organization which distributes the equipment and recordings is therefore anxious to have the services of more voluntary helpers who would be prepared, in their local districts, to maintain the equipment of a few blind people, and make sure it is being used properly.

By reason of the knowledge of its members, the Institution has been especially asked to help in this matter. Members prepared to give a little time to this service should write to the honorary organizer of the voluntary helpers, Mr. D. Finlay-Maxwell, c/o J. Gladstone & Co. Ltd., Galashiels, Selkirkshire.

Comprehensive List of "Sandwich" Courses

The system of technical training known as the "sandwich" course is an important feature of the Government's technical education expansion programme. A list of these courses, which consist of alternate periods of work in industry and at college, has recently been published by the Ministry of Education (H.M.S.O., price 1s. 4d.). It shows the various types of courses offered, where they can be taken, the awards to be gained through them and other relevant information.

The steady rise in favour of the sandwich course can be gauged from the number of courses now available, which has nearly doubled since July last year, rising from 103 to 198. The sandwich course has an advantage over part-time work in that it allows ample time for work of a high academic standard. Many firms now prefer the sandwich course to university training. Nearly 70 colleges in all parts of the country are now offering sandwich courses leading to advanced level educational awards such as the Higher National Diploma or Certificate, or the new Diploma in Technology, to be awarded by the National Council for Technological Awards.

Computer Standardization

Simplifying the field of computer equipment through standardisation is one of the aims of the Data Processing Section which has recently been formed by the Radio Communication and Electronic Engineering Association. Four working parties set up by the Section's technical sub-committee have already gone a considerable way towards the formulation of standards. They are working closely with the British Standards Institution.

One working party has just completed the task of drawing up a chart for work on the many components and nomenclature used in computer fields. Another party is considering standards for tape and will have a specification ready to submit to the B.S.I. before the end of this year. This will cover the requirements of both analogue and digital computers. The production of specifications for an input keyboard and for a simple output device is being dealt with by a third working party. The fourth group is studying information storage cores.

BACK-SCATTER SOUNDING: AN AID TO RADIO PROPAGATION STUDIES*

by

A. F. Wilkins, O.B.E., M.Sc. and E. D. R. Shearman, B.Sc. (Eng.)†

SUMMARY

An historical account is given of investigations of back-scatter, and the evidence indicating the ground as the source is discussed. By means of the radar equation the echo intensity is calculated, and the effects of layer curvature and thickness are indicated. The marked seasonal variations in the echo patterns observed at Slough are discussed. Back-scattering after two or more ionospheric reflections is also considered, while very long distance scattering, sometimes with no intermediate ground reflection, is reported. Tests are described which show that, although good accuracy in skip distance measurement is possible, errors may be high if aerials with a large beamwidth are used. The utility of the rotating-aerial back-scatter sounder with plan position indicator for study of propagation over a wide area is stressed and some samples of records obtained with such an instrument are given.

1. Introduction

In the study of long-distance high frequency propagation, direct measurement of the maximum usable frequency (m.u.f.) for communication over a particular path and of the lengths of successive hops in multi-hop propagation are of considerable importance. Such measurements are difficult to make by conventional means because co-operation is necessary between two observers at opposite ends of the path, sometimes under conditions where reliable communication is impossible. For these reasons the development of the back-scatter technique for the study of long-distance propagation is of great interest, since by this method measurement of skip distance or m.u.f. for any direction of transmission may be made from a single station without any need for the co-operation of a distant observer.

In the back-scatter technique pulses of radio waves are emitted from a directional aerial along the path to be studied (Fig. 1(*a*)). Energy below a certain angle, dependent on the frequency of transmission, is reflected from the ionosphere and returns to the ground at or beyond the skip distance. Most of the energy incident on the ground is reflected onwards in the normal process of multi-hop propagation, but enough is scattered by ground irregularities to permit echoes of the ground pulse to be detected near the transmitter. By measurement of the time delay of the earliest of these echoes to arrive, the oblique range to the edge of the skip zone is determined, and from this, with a knowledge of the layer height, the skip distance may be determined.

A typical echo pattern is shown in Fig. 1(*b*) which shows the transmitted pulse and received back-scattered echoes displayed on a linear time-base. The time-base is calibrated in range assuming that the waves travel at free space velocity, and the oblique range of the echoes can be read off directly.

The quantity most simply determined from back-scatter observations is thus the skip distance at the frequency of transmission. To determine the m.u.f. for single-hop transmission over a particular path, as for point-to-point communication, the frequency of transmission must be varied until the measured skip distance equals the length of the path.

The usefulness of the technique is not, however, limited to the study of one-hop propagation. It is found that, under favourable conditions, echoes are received at greater ranges than are possible for one-hop propagation, successive groups of scatter being seen from ground reflection points at a distance up to a quarter of the earth's circumference.

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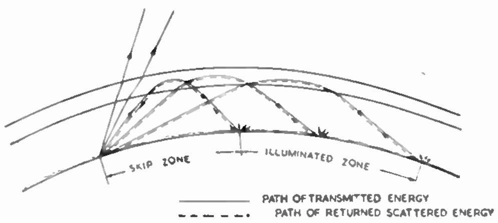
* Manuscript received 11th July 1957 (Paper No. 423.)

† Official communication from D.S.I.R. Radio Research Station, Slough.

U.D.C. No. 621.396.11



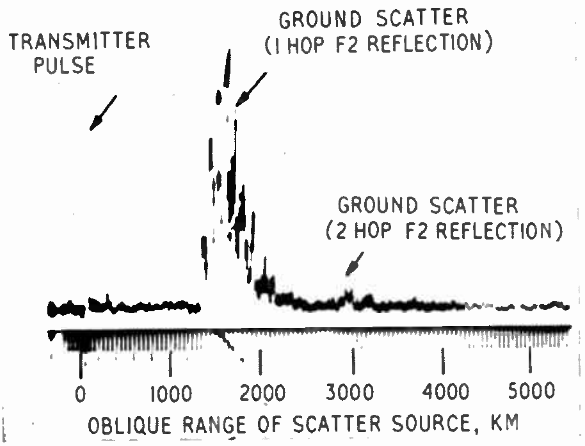


Fig. 1. (*a*) (*above*) Mechanism of back-scatter from ground irregularities.

(*b*) (*right*) Typical scatter pattern for winter noon, 1110 GMT 13th November 1951. Rhombic aerial, directed 80°E of N. Frequency 18·5 Mc/s.

The area of the ionosphere which can be explored can be extended if a rotating directional aerial is used in conjunction with a plan position indicator (p.p.i). The variation of skip distance with azimuth can then be studied, and from this the manner in which the ionization above a large area of the earth varies with time of day can be found. The display on a back-scatter p.p.i. gives a particularly vivid instantaneous demonstration of large scale movements in the ionosphere, and of the resulting changes in the ground areas illuminated, in a manner not possible by any other means.

In this paper the published work on back-scattering is surveyed and the propagation mechanism and characteristics of the scattered echoes discussed. The studies being made at the Radio Research Station to assess the accuracy of m.u.f. measurement for practical application are then described and some interesting new effects mentioned.

2. History

The phenomenon of back-scattering was discovered early in the history of short wave communication but it is only comparatively recently that the mechanism by which it is produced has been explained.

2.1. *Early Work*

The earliest report of the phenomenon appeared in 1927 when T. L. Eckersley[1] concluded, from direction finding observations on comparatively local h.f. transmitting stations, that, in addition to receiving the signal travelling by way of the ionosphere between transmitter and receiver, there was also present a scattered signal the cause of which was not established. In 1926 records of these scattered signals had been made by Mögel and others[2, 3, 4] who found that they were received more strongly on horizontal than on vertical aerials and hence concluded that they had been reflected from an overhead ionized layer the height of which must have been over 1,000 km.

At about the same time Taylor and Young[5], receiving signals from a nearby h.f. transmitter, recorded echoes from ranges of 2,900 to 10,000 km and stated that they "might be thought of as being due to reflections of the wave from rough portions of the earth's surface directly back on itself, so to speak, and coming from the first zone of reflection; namely, from just above the edge of the first skipped distance."

An alternative explanation by Hoag and Andrew[6] was that the echoes were reflections from auroral ionization.

In a later paper Taylor and Young[7] confirmed their previous results and reported that strong back-scattered signals could also be returned from the surface of the sea.

Further work by Eckersley[8] in making d/f observations at Chelmsford on the signals from British beam stations showed that the bearings obtained were more nearly those of the station to which the signals were being sent than those of the sending station. From these results Eckersley concluded that the received energy had been "scattered back from the regions where the main transmitted beam penetrates into the scattering regions of the Heaviside layer." This explanation was later confirmed by Eckersley[9] as the cause of the bulk of the back-scattered energy, but he accepted the possibility that a small proportion of the scattering might originate at the earth's surface.

In 1941 Edwards and Jansky[10] confirmed Eckersley's finding that the echoes were received from the direction of the transmitted beam and also observed the reception of a series of echoes from this direction; the later arriving echoes were at approximate multiples of the delay of the first member of the group. In explanation of this they suggested that the transmitted energy was travelling outwards by a series of hops between earth and ionosphere and that, at each reflection point on the earth, sufficient roughness existed to produce scattered radiation which returned to the vicinity of the transmitter by the path taken on the outward journey.

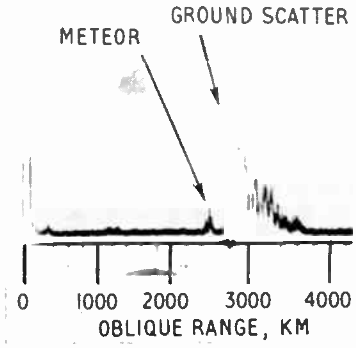
It will be seen from the foregoing that, by about the end of the late war, although there was agreement on some of the aspects of the phenomenon of back-scattering, the difference of opinion as to whether the scattering took place at the ground or at the top of the E-layer had yet to be resolved. The resolution of these differences was important because the practical usefulness of the phenomenon was becoming apparent. Indeed, in 1945, Newbern Smith[11] had proposed the transmission of pulses from a continuously rotating directional array, the reception of the back-scattered echoes on the same array, and their display on a cathode ray oscillograph as in a radar plan position indicator so that the variation with azimuth of skip distance would be observed for the assistance of communication authorities. The practical realization of this idea will be discussed later in this paper.

2.2. *Location of the Origin of Back-scattered echoes*

When investigations on back-scattering were resumed after the war they were, at first, directed mainly toward locating the source of the scattering, and were facilitated by the use of techniques developed for radar.

Kono[12], in Japan, determined that the ground was the source of the scattered signal by comparing the observed time of travel of waves out and back to the transmitting station and the vertical angle of arrival with the values calculated using the height and ionization density observed near the region of reflection of the waves. He also discovered the existence of signal echoes which had been produced by ground scattering of waves arriving after reflection at the sporadic-E layer and returning by the same route.

In the experiments of Hartsfield, Ostrow and Silberstein[13] use was made of a transponder beacon set up at about 2,700 km from a pulse transmitter. Back-scattered signals were received near the transmitter from the direction of the beacon and, in addition, a signal from the beacon whenever it was triggered by the transmitted pulses. From the fact that, for most of the time, the beacon signals coincided in time of arrival with the leading edge of the back-scatter pattern as viewed on a cathode ray oscillograph screen, it was concluded that the back-scattering had originated at the ground. It was also concluded that some scattering originating in the E-layer was also present.



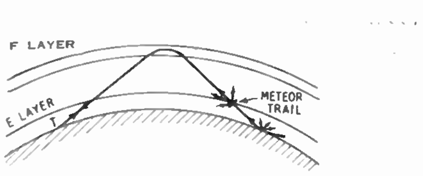


Fig. 2. (*a*) Long range meteor echo, 1130 GMT 14th March 1957. Rhombic 207°E of N. Frequency 22 Mc/s.

(*b*) Mechanism of echo from meteor trail.

Similar experiments were made by Abel and Edwards[14] who found that the whole of the observed back-scattering was produced at the ground and that any echoes received earlier than the amplitude peak near the leading edge of the echo pattern were from sources off the principal direction of transmission of their aerial.

Further evidence that the ground is the source of the scattering has been provided by Dieminger[15], Peterson[16], and Shearman[17]; Peterson concluded that the E-layer could be conclusively dismissed as a source.

An elegant demonstration of the fact that back-scattering occurs at the ground and not at the E-layer is provided by transient echoes from meteor trails which are occasionally seen some two milliseconds before the beginning of the first-received patch of back-scattered echoes propagated by the F2-layer. An example of this phenomenon is seen in Fig. 2(*a*) and a diagram showing the trajectory of the waves is given in Fig. 2(*b*). As the bulk of the ionization produced by meteors occurs in the E-layer at a height of about 100 km, these observations show that the main scattering must occur beyond that layer, and the measured delay between meteor and scattered echo points to the ground as the source. Similar observations of meteor echoes have been made by Hartsfield[18] and by de Bettencourt and Whitcraft[19].

Although it is clear that the ground is the normal source of scatter, Silberstein[20] has described comparisons of m.u.f. over an 1,150 km path deduced by scatter sounding with calculations from vertical incidence soundings in which correlation was closer if E scattering was assumed. The occasions on which this happened coincided with "low latitude ionospheric disturbances," in which the F layer critical frequency was variable, and sporadic E ionization was intense. This mechanism only seemed to be operative at long range, since simultaneous observations at near-vertical incidence showed that ground scattering was dominant at short range. Other explanations of the results could be put forward, however, and further comparisons of scatter measurements with direct measurement of m.u.f. for communication between two points are needed. If such effects can take place, a knowledge of their frequency of occurrence is desirable.

3. Principles Underlying the Propagation of Back-scattered Echoes

The reception of back-scattered echoes from the ground is essentially a radar mechanism, and the methods of analysis used in the study of radar echo propagation are applicable. In the radar problem the amplitude of the echo received from a target is expressed in terms of the power available from the receiving aerial: this is found by considering the inverse square law attenuation of the power flux in the outgoing wavefront, the effective area of the target in intercepting and reradiating energy, and the inverse square law attenuation in the returning wavefront. Line-of-sight propagation, for which the inverse square law is valid, is assumed.

The result of this analysis can be stated in the form of the radar equation which gives, for a target at a range *r*, the echo power available at the terminals of the receiving aerial

$$P_R = \frac{P_T G_T}{4\pi r^2} \cdot \frac{A}{4\pi r^2} \cdot \frac{G_R \lambda^2}{4\pi} \quad \ldots\ldots\ldots(1)$$

where
P_R = available power from the receiving aerial
P_T = total power radiated by the transmitter
G_T = power gain of the transmitting aerial
G_R = power gain of the receiving aerial
(both gains relative to an isotropic radiator)
λ = wavelength
A = echoing area of target.

In the ground back-scatter problem, modifications are introduced by the reflection of the waves from the ionosphere in their travel out to and back from the "targets" which are in fact constituted by the ground irregularities. The echo amplitude is modified by absorption in the lower levels of the ionosphere, and by "focusing" of the energy introduced by the curvature and thickness of the reflecting layer. The propagation is further complicated by the effect of the earth's magnetic field, which splits the radio wave into two components with different polarizations.

The effect of these factors on the characteristics of the received echo pattern and their influence on the interpretation and use of observations have been studied in detail elsewhere[17]. It is proposed here to show first how the characteristics of the received echoes can be calculated for the simplified conditions of a plane earth and plane, thin layer, since the same principles underlie the more complex practical problem. The various influences which modify this simplified picture will then be discussed.

3.1. *Back-Scatter Propagation for a Thin, Plane Layer*

The simplified model which is to be considered is that of the reception of ground back-scatter from irregularities on a plane earth by reflection from a plane, thin ionospheric layer. The model is approximately representative of short range back-scatter propagation by way of the sporadic E-layer.

In this model, all rays leaving a transmitter on the ground at an angle of elevation less than $\sin^{-1}(f_c/f)$, where f_c is the critical frequency of the layer and f is the transmitted frequency, are reflected back to the earth at or beyond the skip distance. Above this angle rays escape through the layer. If the time-base display of the receiver is observed, there is thus a minimum echo range, at which echoes from the skip distance appear, and beyond this, echoes are continuous up to the maximum range of detectability.

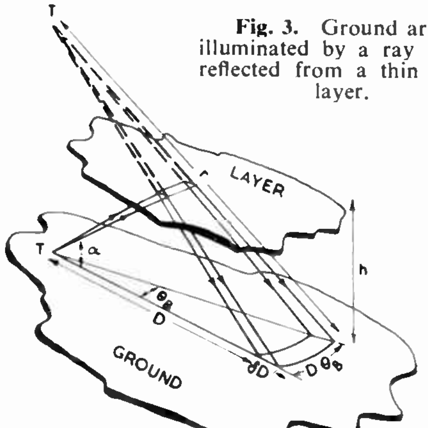


Fig. 3. Ground area illuminated by a ray pencil reflected from a thin plane layer.

In Fig. 3 a pencil of rays is shown leaving the transmitter T and being reflected back to the ground. The field at the ground is the same as that from an image transmitter T′ at a height $2h$ above T, where h is the height of the layer. The problem is therefore the same as that of echoes received from the ground on a radar carried in an aircraft.

For a pulse of duration δt, echoes will be received at any instant from a strip on the ground for which the azimuthal angle, θ_B, subtended is equal to the beamwidth of the aerial, and over which the oblique range changes by $\frac{1}{2}c\delta t$ where c is the free space velocity of radio waves. In the nomenclature of the figure, the area of the illuminated strip is $D\theta_B\delta D$.

For short pulses we can put

$$\delta D = \frac{\delta r}{\cos\alpha} = \frac{\frac{1}{2}c\,\delta t}{\cos\alpha}$$

To find the power scattered from this area, the total echoing area of the scattering sources upon it must be determined. A convenient model for a scattering source is the sphere, which has an echoing area independent of the direction of the incident radiation. The sphere can be represented for vertically polarized waves by a hemispherical boss on perfectly conducting ground.

Let the total echoing area of the bosses on unit area of the ground be A_b. Then the echoing area of the illuminated strip becomes

$$A = D\,.\,\theta_B\,.\,\frac{\frac{1}{2}c\,\delta t}{\cos\alpha}\,.\,A_b \qquad \text{.........(2)}$$

To obtain the received echo power, this value of A is inserted in (1), from which it can be seen that the received echo power is proportional to pulse duration δt. However to find the shape of the echo pattern, we require only the relative amplitude of the received voltage as a function of the range r. For this purpose P_T, A_b, λ and δt can all be considered constant. Initially isotropic transmitting and receiving aerials will be considered, so that $G_T = G_R = 1$ and $\theta_B = 2\pi$.

Hence $$P_R \propto \frac{D}{r^4\cos\alpha}$$

By inspection of Fig. 3, $D = r\cos\alpha$, so that:

$$P_R \propto 1/r^3$$

The deflection produced on the receiver time-base is proportional to the received voltage E_R, which is proportional to $\sqrt{P_R}$, so that

$$E_R \propto 1/r^{3/2}$$

In Fig. 4(*a*), a curve of received voltage against range calculated from this expression is given. A value of 2 has been arbitrarily taken for the ratio of transmitted frequency to the critical frequency of the layer, and a height of 100 km assumed, the value for the sporadic E layer. These values give the skip distance as 346 km and the minimum echo range as 400 km.

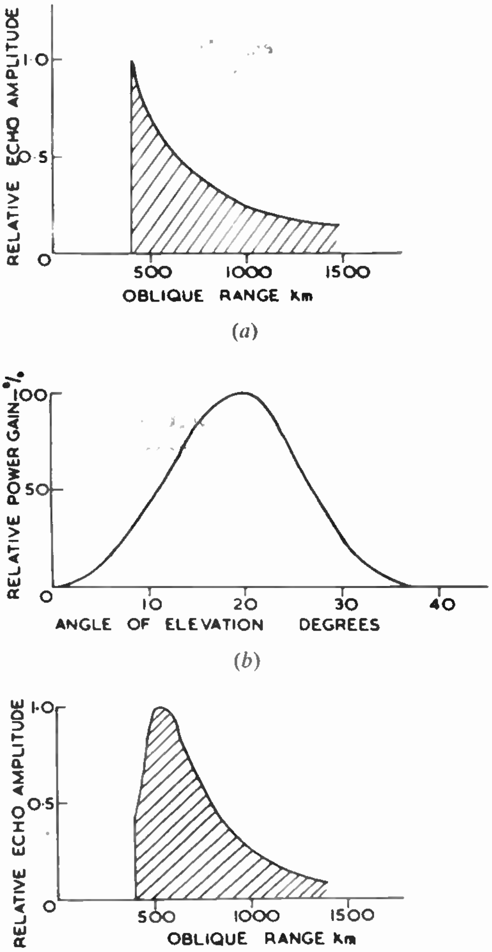


Fig. 4. (*a*) Calculated shape of echo pattern for ground back-scatter reflected from thin plane layer (isotropic transmitting and receiving aerials assumed); (*b*) vertical polar diagram of typical directional aerial; (*c*) echo pattern shape using transmitting and receiving aerials with polar diagram of (*b*).

Figure 4(*a*) represents the shape of the echo pattern seen on the receiver time-base if isotropic transmitting and receiving aerials are used. Such aerials are not practically realizable, and the modifying effect of the vertical polar diagram of a typical directional aerial is shown in Fig. 4(*c*). (The corresponding vertical polar diagram is shown in Fig. 4(*b*).) The aerial, here, has a marked effect on the pattern shape, producing a maximum amplitude 150 km after the leading edge of the echo group.

The pattern shape will depend on the range of the leading edge of the scatter, which is dependent on the ratio of the transmitted frequency to the critical frequency of the layer. Variation of the transmitted frequency will also alter the aerial polar diagram and produce further changes in the pattern shape.

This simple model of back-scattering illustrates certain of the features of the more complicated practical case.

(*a*) The echo group seen on the receiver time-base has a clearly defined leading edge, and the range of this is related to the skip distance. (In this plane-earth example, skip distance $= \sqrt{(r^2 - 4h^2)}$ where r is the range of the leading edge of the scatter group and h is the layer height.) Thus the skip distance can be deduced from a measurement of the range of the leading edge of the back scatter by subtracting a slant-path correction, which at long ranges will be small.

(*b*) For an isotropic aerial, or one with a wide lobe in the vertical plane, the leading edge of the scatter pattern will have the greatest amplitude.

(*c*) The shape of the echo pattern is influenced by the vertical polar diagrams of the transmitting and receiving aerials. If the skip ray is arriving at an angle of elevation higher than that of the main lobe of the aerial, the maximum amplitude of the echo pattern may occur at a greater range than the leading edge. For skip distance measurement the skip echo must always be detectable, so that it is desirable to use an aerial with a good response to rays in the range of vertical angles covered by the skip ray.

(*d*) The strength of the received echo increases with the pulse length. For short pulses the received voltage is proportional to the square root of the pulse length. The same echo amplitude can thus be obtained with a lower peak pulse power if the pulse length is increased to compensate. The upper limit of pulse length is set by the accuracy of range measurement required.

3.2. *Back-scatter Propagation for a Curved, Thin Layer*

The model studied in the last section is representative of back-scatter propagation by way of the sporadic E-layer over short distances. For longer distances the curvature of the earth and the layer become important and produce five principal modifications of the plane earth mechanism.

(*a*) An upper limit of distance for one-hop propagation exists. For a layer height of 100 km, a ray leaving the transmitter at zero angle of elevation would return to the earth at a distance of 2,240 km.

(*b*) The skip distance for a particular frequency is increased, the increase being greater at long ranges.

(*c*) The angle of elevation of a ray returning to the ground at a given ground range is lower than for a plane earth. As a result, the effect of the vertical polar diagram of the aerial will be altered, and maximum and minimum aerial response will occur for different ranges.

(*d*) The relationship between the slant range and the ground range is altered, so that a different correction must be subtracted from the range of the leading edge of the scatter pattern to obtain the skip distance.

(*e*) The curved mirror formed by the ionosphere focuses the radio waves on their outward and return journeys, giving rise to an enhanced field at the distant part of the illuminated zone, and a further enhancement of the returned echoes. The greatest focusing occurs for energy emitted at zero elevation, but this is counteracted by the poor radiation at low angles of practical aerial systems.

The effect of earth and layer curvatures on back-scatter reception is thus to increase the skip distance and consequently also the range of the leading edge of the back-scatter pattern. The trailing edge of the echo pattern is enhanced by focusing, and the peaks and nulls in the pattern introduced by the vertical polar diagram of the aerial will occur at shorter ranges than those for the plane earth model.

For skip distance measurement, however, these are only alterations of detail; the range of the leading edge of the echo pattern is still measured and a correction subtracted to obtain skip distance. The correction necessary for the sporadic E layer has been calculated elsewhere[17] and is given in the curve for $h_m = 100$ km in Fig. 5.

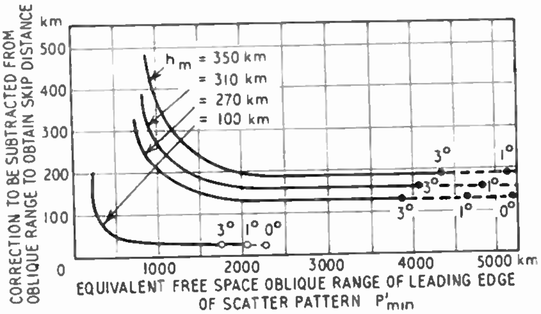


Fig. 5. Chart for determination of skip distance from back-scatter range. The figures given on the curves indicate the angle of elevation of the skip ray.

3.3. *Back-scatter Propagation for a Curved, Thick Layer*

For reflection from a thick layer such as F1 or F2, the situation is more complicated than for a thin layer since the height of reflection changes with the angle at which the ray enters the layer. In addition the energy is slowed down in its passage through the layer so that the assumption of free space velocity of travel is no longer valid. However the relation between the skip distance and the time delay of the first echo is very similar to that for a thin layer, and this relation, if calculated for a suitable model, can be used for skip distance measurement with good accuracy. The model adopted is one in which the relationship between ionic density and height is parabolic; the calculated slant correction to be subtracted from the measured range is given in Fig. 5 for three values of h_m, the height of maximum ionic density.

It is assumed here that the time-base of the back-scatter display is, as before, directly calibrated in range assuming free space velocity of travel. For a thick layer the velocity of propagation varies along the path, so that the range read from the time-base calibration is now only an "equivalent free space range." This is found to be a convenient quantity to use in practice since, for long distance propagation, the equivalent free space range becomes nearly equal to the skip distance. The time-base calibration thus enables a quick estimate of the skip distance to be made directly from the display.

In order to obtain the slant correction from Fig. 5, a knowledge of h_m is needed. It is sufficiently accurate for practical purposes to use the mean value for the time of day and season. If this is not available from a nearby ionospheric observatory, it may be found from the ionospheric prediction charts issued by the Radio Research Station with the help of Fig. 6.

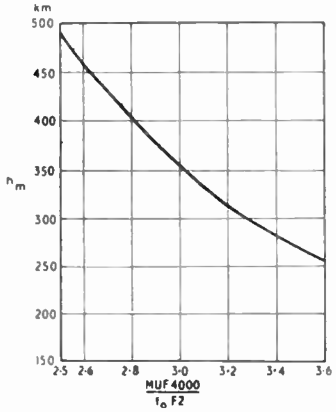


Fig. 6. Relation between h_m and quantities given in ionospheric prediction charts. f_0F2 = ordinary ray critical frequency of F2 layer. M.U.F.4000 = maximum usable frequency for 4000 km path.

The charts give predicted values of ordinary ray critical frequency (f_0F2) and ordinary ray m.u.f. for a distance of 4,000 km. If the ratio $\frac{\text{M.U.F. 4,000}}{f_0\text{F2}}$ is found for the location of the scatter sounder and for the appropriate month and time of day, h_m can be read from Fig. 6.

As a result of the varying degree to which the layer is penetrated, diverging ray pencils emitted from the transmitter at a suitable elevation become convergent after reflection by the layers and form a line of focus on the ground in the neighbourhood of the skip distance. Enhancement of the field strength thus occurs at and somewhat beyond the skip distance and further enhancement takes place for back-scatter returning to the transmitter, resulting in considerably increased echo strength from this range.

Another consequence of penetration into the layer is that echoes from a range of distances are received nearly simultaneously, giving a further enhancement of received echo strength which Peterson[16] has called "time focusing."

To summarize, the thickness of the reflecting layer results in the focusing of energy at the skip distance, and gives the leading edge of the scatter pattern an increased amplitude. The skip distance for a given frequency is increased, and due to the slowing down of the energy in the layer, measurement of the range of the leading edge of the scatter pattern on a calibrated radar time-base yields an "equivalent free space range." However from theoretical calculations made using a suitable model, the correction to be subtracted from the measured range to obtain the skip distance can be found.

The enhancement of the echoes from the skip distance is a fortunate circumstance, since it makes possible the determination of skip distance even when echoes returned from greater ranges are too weak to detect.

4. Characteristics of Back-Scatter Reception

The characteristics of back-scatter propagation have been studied at the Radio Research Station for some years past using a high-power pulse transmitter [21] and either rhombic or Yagi aerials. The behaviour of the back-scattered echoes observed is described below.

4.1. *Seasonal Variation*

An echo pattern typical of back-scatter reception in winter or at night in summer is shown in Fig. 1(*b*) for which propagation is by way of the F2-layer only. It will be seen that intense echoes are received at 1,360 km corresponding to the skip distance for the frequency of operation of 18·5 Mc/s, and that the amplitude of the echoes falls off rapidly with increasing range. The enhancement of echo strength by focusing at the skip distance will be noted. In the same figure a weak echo group may be seen at twice the range of the first group, corresponding to the two-hop focusing referred to later.

The patches of back-scattered echoes correspond to the reception of rays from a large area of ground illuminated by the transmitted beam and it is inevitable, therefore, that some of the rays will be received after similar time delays. The effect of the continuous, short-term changes which take place in the height of the ionosphere is to cause the relative phase between individual rays to vary, leading to interference fading which gives the whole scatter patch the effect of "boiling."

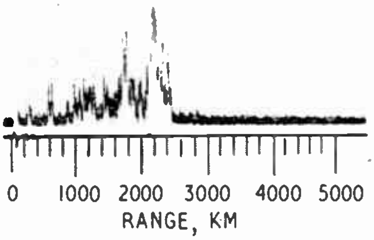


Fig. 7. Scatter pattern for summer noon showing typical complex structure, 8th August 1953. Frequency 13 Mc/s. Rhombic directed east.

Figure 7 shows a complex pattern of the kind observed during the summer day when up to four types of scatter propagation, namely, by way of sporadic E, F1 and F2 layers, may be present simultaneously. In these conditions the scatter groups due to the different modes of propagation overlap, and it is not possible without some additional information such as vertical angle of arrival measurements to determine the skip distance of each mode. These difficulties thus limit the accuracy of interpretation of back-scattering observations made in summer.

The nature of the display of back-scattered echoes received in daytime at Slough begins to change in March from the simple type of Fig. 1(*b*) to the more complex type of Fig. 7 and, in addition to receiving ground scattering propagated by the E, Es and F1-layers, echoes are frequently observed which have resulted from direct transmission out and back to scattering centres in the sporadic E-layer. A statistical presentation of these seasonal changes in the echo pattern has been given elsewhere[22]. Complex scattering persists until about the end of August after which there is a gradual return to comparatively simple conditions.

4.2. *Multiple Echoes*

As has been mentioned earlier, it is possible under favourable conditions to observe groups of scattered echoes from longer ranges than that of the first skip focusing zone. Frequently the ranges of these are approximate multiples of the range of the first group, and thus correspond to the regions of the earth's surface where successive skip focusing zones would occur if the ionosphere were substantially uniform. An example of such behaviour is shown in Fig. 8 which is a 25-hour continuous recording of back-scattering on a frequency of 10·05 Mc/s, obtained with an aerial directed towards the west. During the afternon of 25th November, 1952, three-hop scattering was recorded, the length of each hop being 1,000 km. In the evening the range of the echo groups increased in proportion, and by 1930 G.M.T. all the echoes had faded out. Through the night, apart from a temporary reappearance of one-hop scattering at long range, and the appearance of weak direct echoes from the sporadic-E-layer, no scattering was recorded until 0800 G.M.T. on 26th November, when one-hop scattering appeared at long range and rapidly moved in to 1,000 km range.

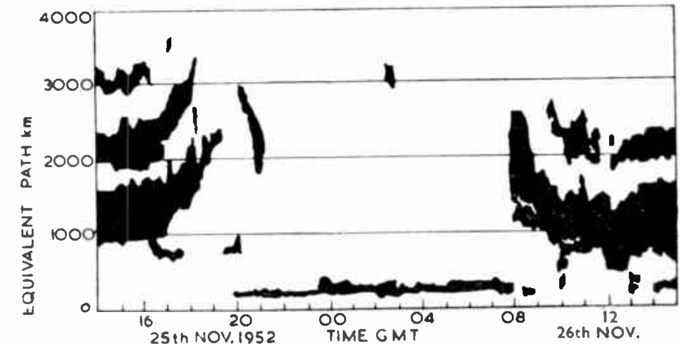


Fig. 8. 25 hours continuous recording of scatter for 10·05 Mc/s transmission. Rhombic aerial directed 289° E of N.

Not all the records obtained, however, show groups of echoes at ranges which are even approximate multiples of that of the first group. Such effects are of considerable importance if the mechanism of long distance propagation is to be understood, and it is proposed to discuss them in more detail.

4.3. *Anomalous Propagation*

On certain occasions in the evening it has been noticed that two groups of back-scattered echoes, apparently corresponding to one- and two-hop F2-layer propagation, have been present at a certain time. Later, however, the first-hop echo has faded out leaving the "second-hop" echo alone for a period until it in turn has faded out. Even more spectacular phenomena of a similar character have been observed during the winter of 1954-55. A range-amplitude record of back-scattering on 19 Mc/s obtained on 23rd February, 1955, using a rhombic aerial directed to the south-east is shown in Fig. 9. This record shows a one-hop back-scattered echo propagated by the F2-layer at an equivalent range of 2,000 km and a two-hop echo at 3,700 km. Following these echoes are three others of small amplitude at 7,200 km, 7,900 km and 8,400 km; all are of doubtful origin except, perhaps, that at 8,400 km which may be a round-the-world echo as it was at that range (i.e. after one sweep of the time-base plus 8,400 km) that such echoes had been identified in the same month. The echo at 10,000 km range which, it will be noted, is of comparable strength to that of the two-hop echo at 3,700 km, is representative of a phenomenon which was observed frequently between December 1954 and February 1955.

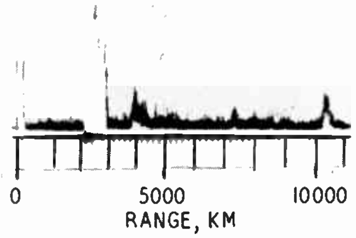


Fig. 9. Scatter pattern showing anomalous long range echo (1620 GMT, 23rd February 1955. Frequency 19 Mc/s. Aerial directed 189° E of N).

On 26th January 1955 back-scattered echoes were received from a range of about 15,000 km in a manner similar to that of the foregoing example; this range would correspond to a source of scattering in Antarctica. On this occasion the strength of the echoes was some 10 db less than that of the two-hop echoes from about 5,000 km range.

An interesting feature of these long-range echoes is that they often persist after the fade-out of the normal one- and two-hop echoes; cases have been observed of such persistence at good strength for up to thirty minutes.

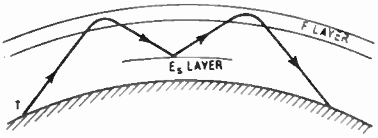


Fig. 10. "M" reflections between Es (or E) and F layers.

The explanation of these cases in which back-scattered echoes are obtained from long distances with apparently no intermediate ground reflection is obscure, partly due to the lack of ionospheric data from the paths concerned. It would appear, however, that the mode of propagation concerned is one in which the attenuation is less than in the normal case of multiple hops between earth and ionosphere. This follows from the fact that the echoes are often stronger than those of, say, the second-hop back-scattering propagated by the F2-layer. One mode of propagation having this property of reduced attenuation is the "M" reflection, where waves travel by one or more reflections between the E- (or sporadic E-) and F-layers as shown in Fig. 10, before returning to the ground. Another such mode involves reflection between tilted areas of the F-layer as in Fig. 11.

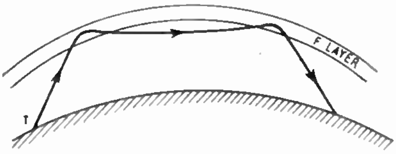


Fig. 11. "M" reflections through the F layer.

The work of Hartsfield[18] is of interest in connection with propagation by M-reflections. In the course of recording back-scattered echoes on 13·7 Mc/s he noted that what appeared to be two-hop ground scattering propagated by the F2-layer was present during the absence of one-hop scattering. At the same time echoes were seen from meteor trails at time delays corresponding to outward transmission by way of the F2-layer, reflection from the meteor trail at the height of the E-layer, and the return of the echo by the outward path as in Fig. 2. He suggested that the E-layer at the time of the observations was a large, smooth and dense area in the region of the meteor; this area would support an M-type trajectory but would not be penetrable by the waves to give normal one-hop ground scattering and it would not produce scattering itself until disturbed by the meteor. This example, while illustrative of the difficulties which may arise in the interpretation of back-scatter records, can hardly be considered as a pointer to the explanation of the present long hops. To obtain hops of 10,000 km and more would involve five or more intermediate reflections from the top of the Es-layer and it seems improbable that this layer would have the properties stated by Hartsfield over such a large area.

Although there is some evidence, at the time of the observations, for the existence of horizontal ionization gradients in the F2-layer of the kind indicated in Fig. 11, there is insufficient ionospheric information for the path concerned to permit firm conclusions to be drawn as to whether this type of trajectory occurred.

It is worthy of note that what may be an example from commercial practice of this same phenomenon of long hops has been given by Smale[23] who reported the reception in Barbados of 11·5 Mc/s signals transmitted from Melbourne, along a great-circle path passing through London, for a period of two to three hours after fade-out of reception in London. He concluded from this result that the signals were reaching Barbados without earth reflection over a considerable part of the route.

4.4. *Dependence of echo strength on terrain*

One negative result of the back-scatter observations at Slough should be mentioned; no marked connection has been found between the nature of the terrain from which echoes are being received and the strength of the echoes. It is possible that careful systematic intensity measurements may reveal, for instance, that echo strength is less from a sea area where there is a flat calm, but in general terrain effects appear to be masked by much larger variations of echo strength due to the variable efficiency of the ionosphere as a propagation medium.

Two workers have reported back-scatter echoes associated with particular geographical features, mountain ranges being identified as the sources in both examples. Dieminger[15], while observing back-scatter echoes at a fixed frequency, identified an echo group which remained at constant range, in contrast to the group associated with the skip focusing area which was varying markedly in range at the time. The range of this fixed echo group corresponded to that expected for scattering from the Alps. Silberstein[20] has shown swept-frequency back-scatter records in which echoes at a fixed range of 2,500 km are present in addition to the skip focusing zone echoes whose ranges increase with frequency. These fixed echoes appeared regularly at about the same slant range, which was correct for the Rocky Mountains.

It is interesting to note that these effects have been distinguished by making use of the high range resolution of scatter sounding equipment. With present aerial beamwidth, especially the wide-beams in use with rotating aerials, azimuthal resolution of geographical features is unlikely to be practicable.

5. Use of Scatter-Sounding to Determine Skip-Distance and Maximum Usable Frequency

The possible use of back-scatter technique in practical signalling to determine the skip distance obtaining on a given frequency or, conversely, the maximum usable frequency for a given distance of communication was first suggested by Smith[11].

Before the technique can be so applied it is desirable to know with what accuracy skip distances can be derived from the back-scatter echo-patterns. There are two important sources of error in such interpretation.

(*a*) Incorrect identification of the modes of propagation. The commonest example of this is the assumption that an echo group has travelled by way of the F2 layer when it has in fact been reflected by sporadic E. The slant path correction applied is then too large, and the skip distance deduced is consequently too small. The F2 layer parameters deduced will also be incorrect and will give rise to a very inaccurate value for the upper limit of one-hop propagation.

(*b*) Reception of echoes from directions off the line of shoot of the aerial beam, for which the skip distance is shorter than along the line of shoot. This will yield skip distances which are too small.

To measure these errors it is necessary to compare the m.u.f.'s or skip distances deduced from back-scatter observations with more direct measurements of these quantities.

Such measurements can be made by recording the field strength arriving from a distant transmitter and observing the times of fade-out and recovery of the signal. At these times, the skip distance is equal to the distance between the transmitting and receiving stations. If back-scatter observations are made at one terminal using nearly the same frequency and employing a directional aerial beamed on the other terminal, the skip distance deduced from the back-scatter range should therefore be equal to the distance between terminals.

Hartsfield and Silberstein[24] used this technique over a path of 2,700 km at a frequency of 15 Mc/s. They reported that there was usually a sudden drop of about 20 db in received signal at fade-out and a corresponding increase at recovery, attributable to the movement over the receiving terminal of the boundary of the F2-layer skip zone. At these times the skip distances deduced from the back-scatter range were found and compared with the true path length of 2,700 km. Errors were within 12 per cent. in summer and within 8 per cent. in winter when the fade-out times were more clearly defined.

The importance of correct identification of the modes of propagation of the echoes was stressed. Sporadic E and F2-propagated echoes were distinguished by their variation with time; the F2-layer scatter was of longer range, and this range varied considerably with the diurnal changes in F2-layer ionization, whereas the sporadic E scatter range did not change much.

It was stated that scattered echoes arriving from directions away from the line of shoot of the aerial and received on side lobes, could be recognized by their appearance on the display.

This same technique has been used in investigations at the Radio Research Station at Slough. The signal strength of a 17 Mc/s telegraph transmission from Malta was recorded, and at the same time the range of back-scatter echoes from a pulse transmission directed towards Malta was observed. A typical pair of records, obtained on 18th June 1954, is shown in Fig. 12. The time scale of the range/time scatter record has been adjusted to coincide with that of the field strength record above it. The lower, shaded, band of scattered echoes represents propagation by sporadic E with an upper limit of range of 1,700 km. The distant, black, band of scatter represents F2-layer propagation, and is seen to exhibit a

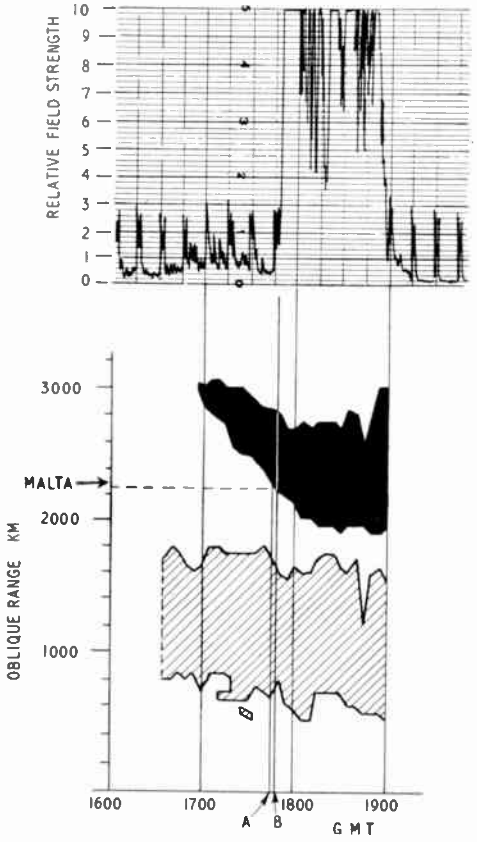


Fig. 12. Comparison of time of recovery "B" of signal received from Malta with time "A" deduced from range of back-scatter. Scatter propagated by F2—Black. By Es—Shaded.

decreasing range during the period of the experiment, corresponding to the temporary decrease in skip-distance in the evening which is a characteristic feature of summer propagation in Europe.

For the F2-layer height prevailing during the experiments, the oblique range of the leading edge of the scatter should have been 150 km greater than the skip distance. The distance from Slough to Malta is 2,100 km, so that the expected scatter range at fade-out or recovery was 2,250 km.

The field strength record shows the presence of a weak signal—presumably propagated by sporadic E or by some scattered mode—during the period 1600-1748 G.M.T. The short quarter-hourly bursts of signal are due to local interference and should be ignored. At 1747½ G.M.T. a very large increase of signal occurred ('B' in the figure), and thereafter the signal remained 20 db or more above its previous level until the transmission ceased just before 1900 G.M.T. The back-scatter range at the time of the sudden increase of signal was 2,230 km, or 0·8 per cent. less than the value of 2,250 km given above. The range reached the value 2,250 km at 1745 ('A' in Fig. 12) so that the error in finding recovery time by back-scatter was in this case only 2½ minutes. Eight observations were made in this series, and the error in scatter range was within 1·8 per cent. for six of these, and 5·5 per cent. for the seventh. The remaining observation showed no sudden increase in signal strength, and no clearly defined F2-layer scatter group. Es-layer echoes were very strong on this day and it was concluded that "blanketing" was taking place, that is reflection from sporadic E of waves which would otherwise have passed through the E layer and been reflected by the F2 layer.

Such accuracies as these are not always possible owing to inadequate aerial directivity, as mentioned at (*b*) above. Thus in deriving the skip distance from the back-scatter pattern, it is not always correct to assume that the echoes forming the leading edge of the scatter come from the bearing of the axis of the main lobe of the horizontal plane polar diagram of the aerial. If the pattern is broad it is quite possible for back-scatter to be received by way of areas of high ionization well off the axis and at ranges shorter than that corresponding to the skip distance along the axis. In such cases the characteristic steep leading edge of the back-scatter pattern, as seen in Fig. 1(*b*), degenerates into a gradual increase in amplitude with range. The low amplitude of the leading edge is due to the reduced response of the aerial off the axis of the beam. In these circumstances great care has to be exercised in interpreting the pattern. The narrower the beam of both transmitting and receiving aerials the less likelihood there is of error, but it is not conveniently possible to build such aerials except for fixed directions.

In the Slough–Malta experiments this source of error was investigated by making observations at intervals with a rotating aerial to obtain information about the variation of skip distance with azimuth. These observations showed that at the times of the experiments the skip distance was at a minimum in the direction of Malta, so that no error from this cause would be expected.

Another experiment was carried out at a later date under conditions where errors due to lack of aerial directivity were expected to be at a maximum. The back-scatter aerial at Slough was directed towards the north, and simultaneous measurements of m.u.f. were made over the 740 km path from Slough to Inverness, using a swept-frequency oblique incidence ionospheric sounder.

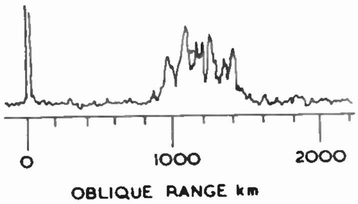


Fig. 13. Scatter pattern showing gradual rise of leading edge associated with off-beam echoes.

Figure 13 is reproduced from a photograph of the received back-scatter pattern at Slough on a frequency of 12·1 Mc/s. The pattern is seen to show the gradual rise expected in the presence of off-beam echoes. Observations with an aerial directed towards the south during this experiment confirmed that the skip distance was less in directions away from the north; the echo pattern here exhibited a sharp leading edge at a shorter range than the northerly echoes.

The pattern of Fig. 13 was obtained at 0912 G.M.T. on 11th January 1957 and a measurement made four minutes earlier by the oblique incidence sounder gave the extraordinary ray m.u.f. for the Slough–Inverness path as 12·1 Mc/s. The scatter observation was thus made at the m.u.f. for the Slough–Inverness path, and the measured scatter range should have been 740 km plus the slant range correction appropriate to this distance and the height of the layer. The measured layer height (h_m) was 330 km giving, from Fig. 5, an oblique range for the leading edge of the back-scatter of 1,050 km. Inspection of Fig. 13 shows that the leading edge of the back-scatter was 830 km, or 20 per cent. shorter than the range expected. It will be noticed that the expected range of 1,050 km coincides with the peak of the echo pattern, providing support for the suggestion that the shorter range echoes come from directions for which the aerial response is poor.

It is concluded from the Slough–Malta and Slough–Inverness experiments that the back-scatter technique can give good accuracy in skip distance measurement provided that the scatter pattern has a sharp leading edge. If the pattern has a gradual rise, however, careful interpretation is required, and the need for improved aerial directivity is indicated.

6. Simultaneous Observation of the Ionosphere over a Large Area by means of the Back-Scatter Plan Position Indicator

A considerable increase in the information given by a scatter sounder can be obtained if the directional aerial is rotated and the echoes presented on a plan position display. Some photographs taken at 17 Mc/s with the equipment at Slough[21] are given in Fig. 14, and show the changes in the display occurring during a single day. The dark areas in the photographs represent the echoes returning from the ground at distances indicated by the 200 km range circles. The location of the ground areas which are illuminated sufficiently intensely to give echoes can be seen from the map. The range to the inner edge of the dark area is the skip distance, from which intense echoes are received, the strength falling off with increase of range until no echoes can be detected. At certain times of day, for example, at 1000 U.T., a second arc of scatter can be seen, corresponding to echoes from the second skip focusing area. (Universal Time = G.M.T.)

The general pattern of ionospheric variation can be seen from the photographs. The ionization of the F2 layer had increased sufficiently to reflect 17 Mc/s waves at about dawn, which occurred first to the east, and gave rise to the echoes seen in the photograph for 0603 U.T. As the day progressed propagation also became possible to the south, west and finally, north. At noon, sporadic E ionization appeared to the west, giving echoes at a shorter range than for F2 propagation. As dusk approached first in the east and then in the west, the scatter range increased until the ionization was no longer sufficient to reflect the waves, and the echoes disappeared. The photograph for 1759 U.T. shows echoes to the south and west only, the ionization to the east being insufficient to sustain propagation.

Many observations of this kind have been made to study variations of the ionization pattern with time of day at different seasons. It has been found that a speeded-up cine-film technique, in which film exposed at one frame per minute is projected at 16 frames a second, gives a very vivid demonstration of these changes. Apart from the regular diurnal changes, large short term oscillations in the skip distance are sometimes seen. The study of these should yield very useful physical information, and should also show what accuracy is likely to be obtainable in the prediction of ionospheric propagation conditions.

7. Conclusions

The examples which have been given of the application of the back-scatter technique show that it provides a powerful means of studying high-frequency propagation. The great advantages of the method are that it dispenses with the need for a distant observer, and that it can give an instantaneous picture of propagation conditions over large areas. The method can be used for studying the ionosphere at points remote from the observing station or to measure quantities of direct practical value to the communication engineer such as skip distance

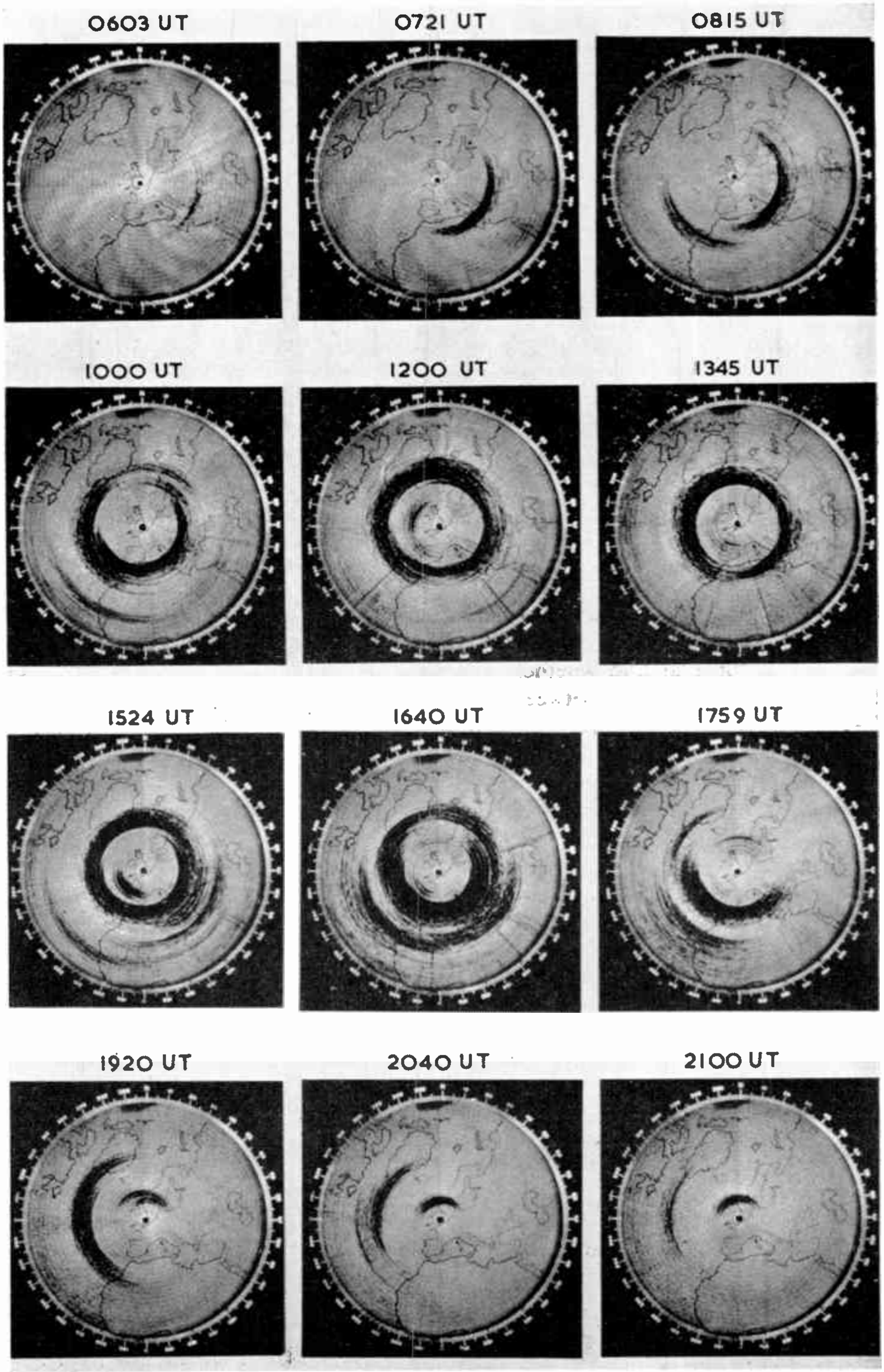


Fig. 14. Variation of back-scattered echoes over the period 0600–2100 UT, 7th October 1954.

or maximum usable frequency for one-hop propagation. In multi-hop propagation the regions where high field strength occur can be found if conditions are favourable, and information about the modes of propagation over long distances can thus be obtained.

Three limitations of present technique may be mentioned all of which might be overcome by instrumental improvements:

(*a*) The accuracy of skip distance and m.u.f. measurement is restricted by the width of the beam of the directional aerials used.

(*b*) The scattered echoes due to different modes of propagation cannot always be distinguished. This might be overcome by measurement of the vertical angle of arrival of the returning energy.

(*c*) Energy is only received from parts of the earth's surface where the incident field strength is high.

This third limitation implies that, although the skip distance can be measured and the areas where multi-hop skip focusing occurs can be found, it is not possible to find whether communication is possible to places between these areas. It is possible that this sensitivity limitation could be overcome by increasing the transmitted power and pulse length, and by integrating the received echoes over a period of time.

In spite of these limitations, the technique in its present state of development should increase considerably our knowledge of long distance h.f. propagation. In particular, the plan position indicator system should contribute to our understanding of large scale geographical and temporal variations in the ionosphere.

8. Acknowledgment

This communication is an extended version of a paper read before the Technical and Traffic Meeting of the Commonwealth Telecommunications Board in 1955. It is published by permission of the Director of Radio Research of the Department of Scientific and Industrial Research.

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RECENT STANDARDS AND SPECIFICATIONS

B.S.2813 : 1957 **Polarized and non-polarized plugs for use on hearing aids.** Price 3s.

The polarized plug is intended for use where the polarity of the current flowing in the earphone or receiver is liable to affect the performance of the hearing aid, but where this effect is unimportant or where no d.c. exists, the simpler non-polarized plug is preferred.

The standard specifies the dimensions which are of importance in achieving interchangeability and other features designed to secure adequate mechanical strength.

The design of the polarized plug follows closely the recommendations agreed by the International Electrotechnical Commission at a meeting in Berne, September 1955, and it is intended that plugs complying with this British Standard shall be interchangeable with those complying with the I.E.C. Recommendation.

B.S.2829 : 1957 **35-mm magnetic sound recording azimuth alignment test films.** Price 2s. 6d.

Specifies a basis for the uniform production of test films for use by manufacturers and users of sound-recording equipment and by service engineers, and relates to 35-mm test film which may be used for the alignment of individual magnetic heads recording within 0·45 in. on either side of the centre line of the film.

Information is given concerning cutting and perforating dimensions, coating, leaders and identification. There is also a section dealing with sound tracks and an appendix giving recommendations for the storage of 35-mm cellulose acetate film.

B.S.2846 : 1957 **The reduction and presentation of experimental results.** By J. T. Richardson. Price 10s.

This new Standard gives guidance on a wide range of types of experiments, e.g. in the laboratory or the factory, in research or in workshop production, in small or large scale observations, or in a series of repetitive tests such as those made for the quality control of products at different stages of manufacture.

A chapter on frequency distribution deals with the grouping and sorting of observations and is useful in presenting the results of large numbers of observations in a condensed form. Details are given of the evaluation and use of the quantities "arithmetic mean" and "standard deviation" for presenting in brief form the results of an experiment, and a variety of examples is included.

Another section of the book deals with the reliability of the results of an experiment expressed in terms of "confidence limits", that is, the limits within which it is estimated that the true values of the "arithmetic mean" and the "standard deviation" lie, when associated with a stated probability. A useful application of the recommended form of presentation of experimental results is described in relation to the repetitive tests necessary for the control of the quality of products during manufacture, using control chart techniques.

B.S.2857 : 1957 **Nickel-iron transformer and laminations.**

The laminations specified in this new Standard are of three standard thicknesses: 0·015 in., 0·008 in., and 0·004 in. There are four classes of material from which they may be made, and for each of the classes and thicknesses, minimum guaranteed permeability figures at 50 c/s are specified, these figures varying with the mean magnetic path. Appendices give test methods for space factor, and for determining—at 50 c/s—the permeability of laminations.

Copies of British Standards may be obtained from the B.S.I. Sales Branch, 2 Park Street, London, W.1.

R.I.C. Specifications

Following the publication of the corresponding British Standards the following R.I.C. Specifications are now regarded as obsolescent:

R.I.C./131—Capacitors, Fixed, Paper Dielectric, Tubular Foil. (Replaced by B.S.2131 : 1956).

R.I.C./214—Transformers, Power, up to 2 KVA Rating. (Replaced by B.S.2214 : 1955).

R.I.C./1000/C—Standard Colour Coding for Connections in Radio and Electronic Equipment (other than domestic radio and television). (Replaced by B.S.2311 : 1955).

Details of the British Standards were given in the August 1956 issue of the *Journal*.

"Ceramic Insulators for Telecommunication Purposes"

This specification, prepared by the Radio and Electronic Component Manufacturers Federation, has recently been revised by the Federation's Panel "R" and is published from 21 Tothill Street, London, S.W.1, price 1s.

The classes of ceramic materials to which the specification refers are general insulators (e.g. porcelain, permittivity 5 to 7), h.f. insulators (e.g. steatite, permittivity 5 to 10) and dielectrics for capacitors (permittivity 5 to 300). Tolerances for various dimensions of insulators are stated and an appendix puts forward a number of points of good design practice.

FILMS ON AUTOMATION

A list of instructional films on a variety of topics was published in the *Journal** last year in connection with a report of a Discussion Meeting on "The Importance of Visual Aids in the Teaching of Advanced Radio and Electronic Engineering." During recent months new films have become available, many of them on the broad subject of automation. A selection of those likely to be of the greatest interest to radio and electronics engineers is listed below. Acknowledgment is made to the Scientific Film Association for assistance in compiling this list.

All the films listed are 16 mm, with sound, unless otherwise stated. Application should be made to the distributors concerned for further information, including arrangements for loans.

AUTOMATION IN COMPONENT TESTING
Producer and Distributor: J. A. Sargrove, Automation Consultants and Associates Ltd., 341/9 Oxford Street, London, W.1 (1957). Silent, 13 mins.
Describes the Automatic Component Testing Equipment (ACTE) developed for the Royal Radar Establishment. The equipment permits a prolonged cycle of climatic tests to be applied to a "type-approval" batch of 1,000 resistors.

AUTOMATION IN PRODUCTION
Producer: Karl Huller, G.m.b.H. *Distributor:* Publicity Department, Burton, Griffiths and Co. Ltd., Mackadown Lane, Kitts Green, Birmingham 33. 75 mins.
The machining of automobile components is shown. Sequences in turn deal with an indexing table, drum-type and in-line machines, and a 37-station transfer line for machining gearbox housings.

AUTOMATION IN TELEVISION
Producer: Atlas Film Corporation (1955). *Distributor:* Admiral Corporation, Public Relations Department, 1191 Merchandise Mart, Chicago 54, Illinois. 10 mins.
Automatic machines used in the production of radio and television receivers are shown; these machines insert resistors, wire jumpers, upright capacitors, valve holders and wafer capacitors in printed circuits, some 600 components in all.

DYNASERT AUTOMATIC ASSEMBLY MACHINERY (PART I)
Producer: The United Shoe Machinery Corporation, Boston, Massachusetts (1955). *Distributor:* Geo. Tucker Eyelet Co. Ltd., Walsall Road, Birmingham 22. 7 mins.
Describes equipment for assembly using printed wiring boards, standard components and dip soldering techniques.

DYNASERT AUTOMATIC ASSEMBLY MACHINERY (PART II)
Producer: The British United Shoe Machinery Co. Ltd. (1956). *Distributor:* As for Part I. Silent, 3 mins.
Illustrates British equipment developed for automatic insertion of electronic components into printed circuits.

DYNASERT AUTOMATIC ASSEMBLY MACHINERY
Producer: The United Shoe Machinery Corporation, Boston, Massachusetts (1956). *Distributor:* As for Parts I and II. Silent, 20 mins.
This film describes the subsequent development of the system dealt with in the two previous films. Its circulation is restricted as the distributors consider an expert commentator essential.

ELECTRONIC CONTROL—NEW POWER IN INDUSTRY
Producer and Distributor: J. A. Sargrove, A.C.A. Ltd., 341/9 Oxford Street, London, W.1. (1956) Silent, 25 mins.
Examples from widely differing industries are: automatic stock-keeping; inspection for correct lay of paper; guiding of multi-layer paper alignment; control of nylon stentering; control of plastic extrusion; weighing of dough balls and control of dough divider in a bakery; counting and batching of pharmaceutical tablets.

NUMERICAL CONTROL
Producer and Distributor: Ferranti Ltd., Ferry Road, Edinburgh 5. (1956) 20 mins.
Describes the Ferranti system for the computer control of machine tools including the philosophy of the system. The drawing, planning, computing and machining of a particular part is discussed.

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* *J.Brit.I.R.E.*, **16**, pp. 544-522, October 1956.

FERRORESONANT CIRCUITS FOR DIGITAL COMPUTERS*

by

C. B. Newport, B.Sc.† and D. A. Bell, M.A.,Ph.D.†

A paper presented at the Convention on "Electronics in Automation" in Cambridge on 27th June 1957. In the Chair: Dr. A. D. Booth (Member).

SUMMARY

The characteristics of the ferroresonant circuit are analysed and conditions for bistability obtained. Problems of high frequency operation are considered and the composition and configuration of suitable ferrites discussed. A carrier frequency of 1 Mc/s seems to be the present limit. Practical circuits are presented for a shift register, 3-stage binary counter and 2-input logical adder.

1. Introduction

Most electronic computers work on the binary scale, so that the representation of a digit value requires only a two-state element. The digit value is to be "read" by an electric circuit, which, in fact, requires an energy many times that which suffices for the human eye to distinguish between, say, black and white, and a major problem is the tendency for the operation of reading the digit value to destroy the record. Then one may divide storage devices into the three groups of passive, regenerative, and active stores, each having its own advantages and disadvantages. The most obvious passive stores are the matrix of magnetic toroids and its ferroelectric analogue, but magnetic tape, and, in fact, the magnetic drum as well, are quasi-passive: the information remains static on the magnetic medium, but motion of the medium relative to the pick-up head is usually employed to provide a substantial output with negligible destructive effect on the static record.‡ The last point is important, for a weakness of the toroid matrix is the necessity to destroy the record in order to extract information from a core. Regenerative stores such as acoustic lines and the Williams cathode-ray-tube store have the advantage of employing a very small physical element for each bit stored, but require more complex circuits. The obvious active bistable system is the two-valve (or one-transistor) flip-flop, but the ferroresonant circuit to be discussed in this paper is another active circuit. Together with the advantage of being able to read out information without destroying the record, both regenerative and active stores have the disadvantage that a supply failure will cause loss of the record, whereas the passive stores are not dependent on power supply for the retention of the information. The advantages one obtains from the ferroresonant circuit as compared with the pair of valves are reliability, low power dissipation, small size and cheapness, though if the transistor fulfils all the hopes which have been held out, cheapness may be the only remaining virtue of the ferroresonant circuit.

2. Analysis of the Ferroresonant Circuit

For many years it has been known that it is possible to make a resonant circuit exhibit two stable states if the inductor is non-linear. This phenomenon is known as ferroresonance and while it has been undesirable in many cases, Suits[1] and others have shown how it could be put to use in non-mechanical relay circuits.

Bistability as a consequence of a nonlinear inductor is possible either in a series resonant circuit (Fig. 1) fed with a constant voltage, or a parallel resonant circuit (Fig. 2) fed with a

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* Manuscript received 13th March 1957. (Paper No. 424.)

† Electrical Engineering Department, University of Birmingham.

U.D.C. No. 621.318.42:681.142.

‡ See, however, T. Kilburn, "Reading of magnetic records by reluctance variation," *Proc. Instn Elect. Engrs*, **103**, Part B, Supplement, p. 233, 1956.

constant current. These series and parallel circuits are duals of each other so only one need be considered in detail.

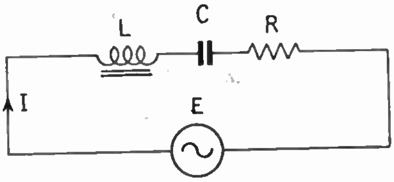


Fig. 1. Series resonant circuit.

Exact analysis of these non-linear circuits involves great mathematical complexity. The series circuit has been analysed in detail by Keller[2], but fortunately detailed analysis is not necessary in the present work and an approximate analysis, involving only the fundamental components of current and voltage, is sufficient. This is because the Q of the resonant circuit is usually sufficient to ensure that the voltage across a parallel-resonant circuit (or current in a series circuit) remains sinusoidal. Throughout this paper fundamental components only are implied unless otherwise stated.

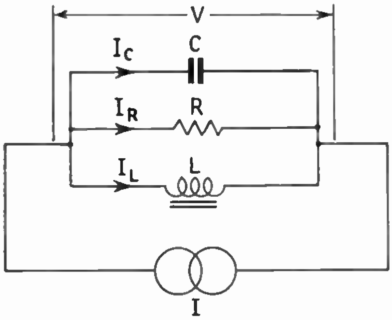


Fig. 2. Parallel resonant circuit.

2.1. *The Inductance/Voltage Characteristic*

If we consider a parallel resonant circuit in which the inductance is variable and which is fed by a constant current, we can plot a curve of the r.m.s. voltage across the circuit as the inductance is varied through the resonance value, the other parameters being kept constant. This is curve (*a*), Fig. 3, and has the equation:

$$V_{\text{r.m.s.}} = \frac{I_{\text{r.m.s.}}}{\left[\frac{1}{R^2}+\left(\frac{1}{\omega L}-\omega C\right)^2\right]^{\frac{1}{2}}} \quad \text{.........(1)}$$

On the same graph we can superimpose a curve showing how the inductance of the non-linear inductor changes with the voltage across it. The inductance of a non-linear inductor is defined for our purpose as the inductance measured on a bridge balanced for the fundamental frequency when the bridge is providing a given r.m.s. voltage across the inductor. The instantaneous inductance is, of course, changing over the cycle and this will produce harmonics at the bridge detector but these are filtered out and only the fundamental is considered, on account of the resonant nature of the circuit. The frequency of measurement is the same as that at which the ferroresonant circuit will operate.

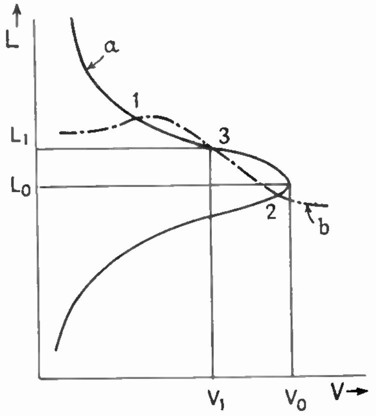


Fig. 3. Plots of inductance versus voltage:
(*a*) for a resonant circuit with constant frequency of excitation, constant capacitance and constant total current;
(*b*) for an iron-cored inductor at constant frequency but variable current.

These measurements will give us a curve of inductance against r.m.s. voltage:

$$L = f\,(V_{\text{r.m.s.}})$$

or we can transpose it to read:

$$V_{\text{r.m.s.}} = g\,(L) \quad \text{.........(2)}$$

The actual r.m.s. voltage V, which exists across the circuit of Fig. 2 must satisfy both equations (1) and (2), and so it is determined by the intersections of the two curves on Fig. 3. These curves either intersect in one point, in which case the circuit is not bistable, or in three points as shown. Points 1 and 2 represent stable conditions of inductance and voltage and the third is unstable.

This graphical approach, or the similar

approach suggested by Odessey and Weber[3] enables an approximate analysis of the circuit to be made and the voltages at the stable points to be determined.

2.2. *The Reactive Current/Resistive Current Characteristic*

In practice, both the above graphical representations are very tedious to use to obtain numerical results. The curve of inductance against r.m.s. voltage is simply plotted from experimental measurements but the calculation of the resonance curve is very tedious, particularly if a family of curves is required for various values of current and capacitance. This is made more difficult because neither the equivalent parallel resistance nor the Q of the circuit, $\omega L/R$, is constant for any practical circuit, and this prevents the use of normalized resonance curves.

A far simpler representation has therefore been developed which enables the points of intersection to be quickly determined.

Firstly, the resonant circuit curve (in r.m.s. values) for the parallel circuit of Fig. 2 is:

$$I_L = \left[I^2 - \left(\frac{V}{R}\right)^2 \right]^{\frac{1}{2}} + I_C$$

where I_C is the capacitor current.

$$\text{Therefore } (I_L - I_C)^2 = I^2 - \left(\frac{V}{R}\right)^2$$

Now $(I_L - I_C)$ is the sum of the current in the inductor and the capacitor (they are 180 deg. out of phase) and may be written as I_{LC}

$$\text{Hence } I^2_{LC} + \left(\frac{V}{R}\right)^2 = I^2 \qquad \text{.........(3)}$$

Hence if we plot I_{LC}, the reactive current, against (V/R), the resistive current, we simply get a circle of radius I. This is the resonant circuit curve (*a*) of Fig. 4, and its shape is independent of the specific experimental data.

To obtain the inductance curve we use the experimental data which, for discrete values of V, give corresponding values of L and R. Thus we can easily calculate the values of V/R. To obtain I_{LC} we note that:

$$I_L = \frac{V}{\omega L} \text{ and } I_C = V\omega C$$

$$\text{Thus } I_{LC} = I_L - I_C = V\left[\frac{1}{\omega L} - \omega C\right] \qquad \text{.........(4)}$$

We have, in the experimental results, tabulated values of V and L for each value of V/R, and as ω and C are known parameters, we can rapidly calculate the values of I_{LC} corresponding to each value of V/R.

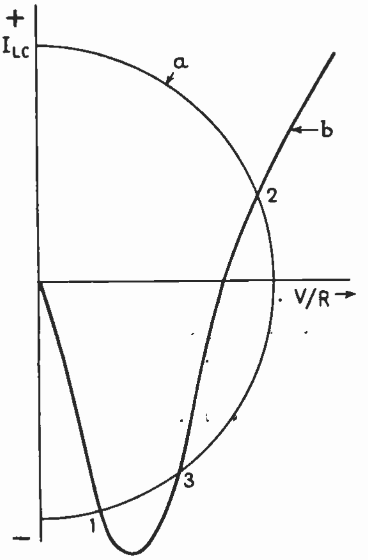


Fig. 4. Plots of reactive current versus resistive current:

(*a*) for a resonant circuit at fixed current, frequency and capacitance but variable inductance;

(*b*) for an iron-cored inductor at constant frequency but variable current.

Then by plotting I_{LC} against V/R we obtain the inductor curve (*b*) of Fig. 4, the circuit requirements being satisfied by points 1, 2 and 3, of which 1 and 2 are stable and 3 is unstable.

This graph gives the values of V/R at the stable points, and to find the actual value of V we use the relation between V/R and V which has already been tabulated during the calculation of I_{LC}. The stable values of voltage across the circuit can then be read off.

We are also interested in the way in which the parameters I and C affect these stable voltages. The effect of various values of I can be very simply determined by drawing a family of circles of different radii and noting the change in position of the intersections of the circles with curve (*b*). To observe the effect of various values of capacitance, slightly more work is necessary as a new (*b*) curve must be calculated and plotted for each value of capacitance. Nevertheless, using equation (4) it only means subtracting a different, constant, value from the already tabulated values of I/L, and a family of inductor curves can be quickly drawn.

2.3. *Determining whether Bistability is possible*

The above graphical procedures are useful if we require a more or less complete, steady state, analysis of a given circuit, but if there are many non-linear inductors it is convenient to have a quick test to decide whether a given inductor has a sufficiently non-linear characteristic for it to be usable in a ferro-resonant circuit.

To develop this technique we return to the inductance-voltage characteristics of Fig. 3. From these two curves it can be seen that if an intersection such as point 3 exists, then points similar to 1 and 2 must exist, and the circuit will be bistable. Point 3 is characterized by the rate of change of coil inductance with voltage being greater than the rate of change of circuit inductance, while both changes are in the same direction. Thus to determine whether bistability is possible we have only to determine whether it is possible to choose values of capacitance and supply current to make an intersection such as 3 exist. The optimum position (V_1, L_1) of point 3 can be defined as that position which will give bistability with the least possible inductor non-linearity. This position will occur when the point of maximum rate of change on the coil inductance curve corresponds with the point of minimum rate of change on the resonant circuit curve. That is, the points of inflection on both curves must be arranged to coincide and if the maximum slope of the coil curve then exceeds the minimum slope of the circuit curve, bistability will be possible. In practice, it is simpler mathematically to work in terms of the reciprocal of the slope, i.e. ($\mathrm{d}V/\mathrm{d}L$), and so for bistability we require that $(\mathrm{d}V/\mathrm{d}L)_{\min}$ of the coil is less than $(\mathrm{d}V/\mathrm{d}L)_{\max}$ of the circuit at point 3 where $V=V_1$ and $L=L_1$.

Thus the procedure for testing for bistability is:

(1) Obtain the inductance-voltage characteristic of the coil at the frequency at which it is to operate and then determine (*a*) the minimum value of ($\mathrm{d}V/\mathrm{d}L$) coil, say $(\mathrm{d}V/\mathrm{d}L)_{CL}$, and (*b*) the position (V_1, L_1) of this minimum. This defines the optimum position of point 3.

(2) Now a circuit curve must be found which has its maximum value ($\mathrm{d}V/\mathrm{d}L$) at V_1, L_1. The value of inductance at which the maximum value of $\mathrm{d}V/\mathrm{d}L$ occurs in a parallel resonant circuit is given by:

$$\frac{L_1}{L_0} = 1 + \frac{3}{4Q^2} \pm \frac{1}{4Q^2}(9+8Q^2)^{\frac{1}{2}} \quad \text{.........(5)}$$

The positive sign must be taken if the coil inductance is decreasing with voltage and the negative sign if it is increasing. Q is defined in the usual way as $\omega L/R$, and L_0 is the inductance at resonance, i.e. $1/\omega^2 C$. As Q is variable the value taken must be that derived from the measured values of resistance and inductance at V_1, L_1.

The form of (5) assumes that the slope of the tuned-circuit curve is not affected by the fact that Q itself is varying over the resonance curve. This is a reasonable approximation, since the point of inflection occurs where the reactance is becoming the dominant factor. A trial value of Q for the anticipated value of L can be used in (5) in the first place, and a second approximation taken if L_1 is far enough from the value guessed for Q to be significantly different.

From equation (5) above, the value of L_0 can be found by putting in the measured value of Q and then setting L equal to the known value of L_1. Hence knowing L_0 the required value of C can be found.

(3) To test whether bistability is possible the actual value of the slope of the coil curve at V_1, L_1 must be found. This entails calculating V_0, the voltage at resonance, from the equation:

$$\frac{V}{V_0} = \frac{1}{Q}\,\frac{L/L_0}{[(1-L/L_0)^2+1/Q^2]^{\frac{1}{2}}}$$

V_0 is obtained by substituting the above values of Q and L/L_0, and putting $V=V_1$.

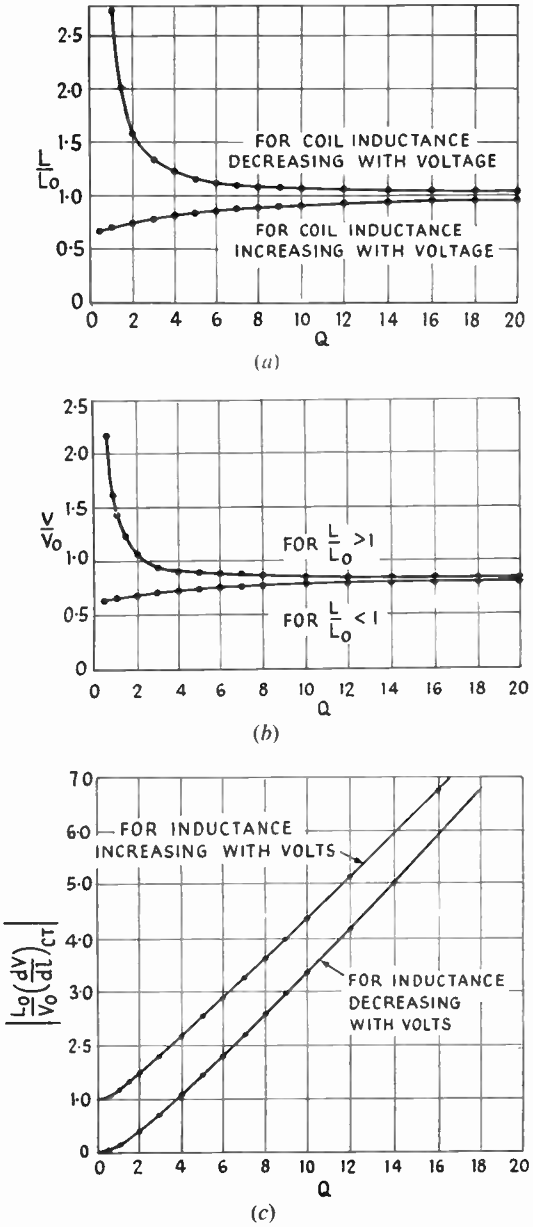
The resonance curve is now fixed with its maximum of ($\mathrm{d}V/\mathrm{d}L$) occurring at point V_1, L_1. The value of this maximum is given by:

$$\left(\frac{\mathrm{d}V}{\mathrm{d}L}\right)_{ct} = \frac{V_0}{L_0}\,\frac{1-L_1/L_0+1/Q^2}{Q[(1-L_1/L_0)^2+1/Q^2]^{3/2}}$$

If this value is greater than $(\mathrm{d}V/\mathrm{d}L)_{CL}$, defined above, then the circuit curve will intersect the inductor curve in three points and bistability will be possible.

As L/L_0 is a function of Q only, curves can be plotted giving L/L_0, V/V_0 and L_0/V_0

$(\mathrm{d}V/\mathrm{d}L)_{ct}$ as functions of Q and these enable us to determine very quickly the values of L_0, V_0 and $(\mathrm{d}V/\mathrm{d}L)_{Ct}$. These curves are shown on Fig. 5.



(*a*)

(*b*)

(*c*)

Fig. 5. Dependence on Q of the position of the point of inflection on the resonance curve:
(*a*) critical inductance as fraction of resonant inductance;
(*b*) critical voltage as fraction of resonant voltage;
(*c*) normalized slope of resonance curve at the critical point.

To obtain further information from this bistability test the slopes of the two curves on either side of the optimum position can be compared. A number F can be defined, such that:

$$F=\frac{(\mathrm{d}V/\mathrm{d}L)_{Ct}}{(\mathrm{d}V/\mathrm{d}L)_{CL}}$$

and then if the point 3 intersection occurs anywhere in the range where F is greater than unity, bistability will be possible.

This test gives no indication of the voltage discrimination between the two stable states, and, in fact, to determine this reasonably accurately necessitates the use of one of the graphical procedures outlined above. Obviously this discrimination is some function of Q, a high Q circuit giving a high discrimination and vice versa, so as an approximate figure of merit we can take the product of F and Q. This figure of merit FQ will help to select the non-linear inductor which is likely to have the greatest stability in each state and the largest discrimination between stable states when used in a ferroresonant circuit. When F is less than 1 the figure of merit must be taken to be zero.

3. Ferroresonant Circuits for High-Frequency Operation

3.1. *Excitation Frequency*

In order to establish a reasonably rectangular envelope, one must allow 5 to 10 cycles of excitation per digit pulse, and in order to compete with existing stores for high-speed electronic computers, e.g. 3 microsecond pulses in nickel delay lines and 1 microsecond pulses in mercury, the excitation frequency of the ferroresonant circuit would have to be between 1·5 and 10 Mc/s. Mu-metal strip cores have been very successful at excitation frequencies of a few tens of kilocycles, but eddy currents cause difficulty at higher frequencies for two reasons: the core losses increase, and the use of thinner strips reduces the effective volume of magnetic material in the core unless one is prepared to stack together a number of thin laminations. Some experiments were therefore directed to the use of ferrites in place of metal for the saturable core.

3.2. *The Use of Ferrite Core Materials*

Many ferrites have very low conductivity so that the eddy currents are negligible, but they are magnetically harder than mu-metal and so require more drive in terms both of volt-amps and of hysteresis loss. Tests have been made on various grades of manganese and nickel and magnesium ferrites, and it is found that the hysteresis loss sets the limit to the frequency of operation. Tests to separate the losses were made on a toroidal specimen of an experimental magnesium-zinc ferrite supplied by the Plessey Company and having the composition number M 40/1400. These tests indicated that at a frequency of 1 Mc/s and with one volt across the coil the losses were about 81 per cent. hysteresis loss and 19 per cent. eddy current loss. The losses were too great at 1 Mc/s to allow saturation to be reached, for at a driving field which took the coil just beyond its peak value of inductance the core began to get hot due to the large loss within it, and as the temperature rose towards the Curie point the coil inductance decreased to a very small value.

As a ferrite having lower hysteresis loss was unavailable at the time, the only way to avoid the effect of the large hysteresis loop was to make it unnecessary to trace out the whole loop during each cycle. This was accomplished by applying a steady bias field so that the applied high frequency field took the core into deep saturation in one direction but just back to the high permeability section of the *B-H* loop in the other direction. This gave a definite improvement over the unbiased case and bridge measurements of inductance and *Q* versus coil voltage indicated that it should produce a bistable resonant circuit at 1 Mc/s. It was in fact just possible to demonstrate experimentally the bistable behaviour of a circuit incorporating this inductor, but the internal temperature rise caused the working point to drift so that the circuit was not usable. (In the parallel-tuned ferroresonant circuit, this drift gives rise to a thermal relaxation cycle between the high- and low-amplitude conditions, a cycle which in this specimen had a period of about five seconds.)

The hysteresis loss of the M 40/1400 material, measured at low frequency, was 150 ergs/cm^3/cycle. There are some ferrites with lower hysteresis loss, but such as are known to the authors have relatively high conductivity which would give rise to prohibitive eddy-current losses at 1 Mc/s.

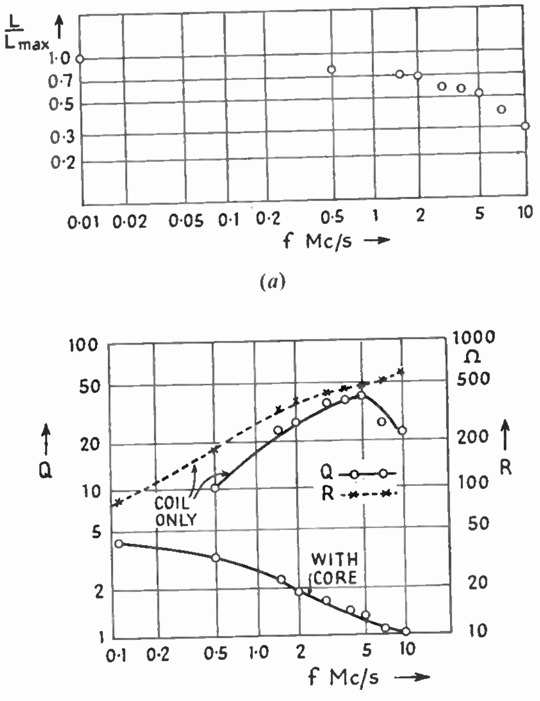
The desirable characteristics are clearly low loss and a rapid transition from high permeability to saturation. Williams *et al*[4] have shown that if ferrites which have negative magnetostriction are subjected to a compressive force, the hysteresis loop takes on a rectangular shape so that the maximum incremental permeability is increased and the transition to saturation made much more abrupt. Although this phenomenon has been demonstrated on a toroid of Ferroxcube B.2, the authors have not succeeded in making use of it in bistable circuits, where the relevant factor is the average permeability over a hysteresis cycle.

A material which shows a large change of a.c. permeability for small currents is the high-coercivity square-loop ferrite such as the Ferroxcube D.1 grade. This is because a field intensity less than the coercive force has little effect on the flux, and the material therefore appears to have negligible permeability for such small fields; but when the field is sufficient to cause reversal of flux, there is a sharp increase in effective permeability. But the hysteresis losses are naturally very great, and the resulting low *Q* has so far prevented the use of this material in ferroresonant circuits.

3.3. *High-Permeability Metal Strip Cores*

The ferroresonant circuit requires a large change of inductance with applied voltage, as well as low loss, and in principle any magnetic field in air is wasted. Hence the toroidal core, in which with low frequencies and high-permeability material practically the whole of the flux is confined to the magnetic material, appears to be the ideal. A toroidal inductor is, however, more difficult to wind than a straight-cored inductor, and it has been found technically sound to use cores consisting of straight strips of metal. A magnetized strip has poles near the ends which produce a field in opposition to the applied magnetizing field and thus reduce the apparent permeability. But if the strip is long enough in proportion to its diameter the demagnetizing effect of the poles is insignificant and the apparent permeability of the central part of the strip is practically equal to the full permeability of the material. Bozorth[5] has published charts and tables showing the relation between apparent permeability, length/diameter ratio and true permeability for cylinders, and these can be used to give a rough estimate for strips if the geometric mean of strip width and strip thickness is substituted for diameter of cylinder, or a close equivalence if the strip is rolled into a hollow cylinder as is sometimes convenient. Given suitable lengths of strip, therefore, strip cores are just as effective as toroids. Since high-grade mu-metal has a permeability of the order of 50,000 to 100,000, the necessary length/diameter ratio would be prohibitive if it were desired to retain this full value. But it was argued that since the material would be used at the highest frequency permitted by eddy currents, the apparent permeability of a core would in any case be less than the zero-frequency value, and one might as well take a length/diameter ratio appropriate to the permeability which could in practice be achieved. Another way of looking at it is that if the effective permeability is going to be reduced both by eddy-currents and by end-effects, there is no point in making the latter effect too much less than the former. The type of strip used in practice has been between ½ in. and 1 in. long, around 1/16 in. wide, and less than 0·001 in. thick. It is well known that when full skin effect occurs, the mean e.m.f.'s due to resistive and reactive effects are equal, so that the current in the surface has an effective phase-angle of 45 deg. and the Q of the piece of metal, regarded as an energy store, is approximately unity. This is independent of the permeability of the material, for an increase in permeability reduces skin depth as well as increasing magnetic energy density $\frac{1}{2}\mu H^2$ for fixed magnetomotive force. It is therefore essential to work with strips which have been rolled thin enough to secure some reduction of eddy-current loss, i.e. the thickness of strip must be of the same order as the skin depth.

Initial calculations based on the formula for depth of penetration of an alternating magnetic field into an infinite plane sheet of material having the permeability of mu-metal were very discouraging: the implied strip thickness was of the order of 200 angstrom units. However, the failure of the ferrite line of approach led to an experimental examination of the behaviour of metal strips, and material was provided by the Post Office Research Station at a thickness of 8 microns (approximately 0·0003 in.). Two alloys so far examined are designated JZ (77% Ni; 14% Fe; 5% Cu; 4% Mo) and FO which is a special alloy having a Curie point of about 100°C. The low Curie point of the latter is in some ways a practical disadvantage but it is incidental to the production of an alloy having a low value of saturation flux with high permeability. Fig. 6 (*a*) shows the variation with frequency of the apparent permeability of this material, i.e. the ratio of inductances of a test coil with and without the metal strip, and Fig 6 (*b*) shows the variation with frequency of the shunt resistance and Q of the coil with this core. On the score of apparent permeability this core would be usable up to at least 5 Mc/s and possibly 10 Mc/s, and the total losses are the limiting factor.



(*a*)

(*b*)

Fig. 6. (*a*) $L_{\text{iron}}/L_{\text{air}}$ versus frequency for coil with core of FO alloy.

(*b*) Shunt resistance and Q versus frequency for coil with core of FO alloy.

By comparison with infinite-slab theory, it is clear that the limited length and width of the test specimen had a marked effect on the eddy-current loss; and a series of tests to

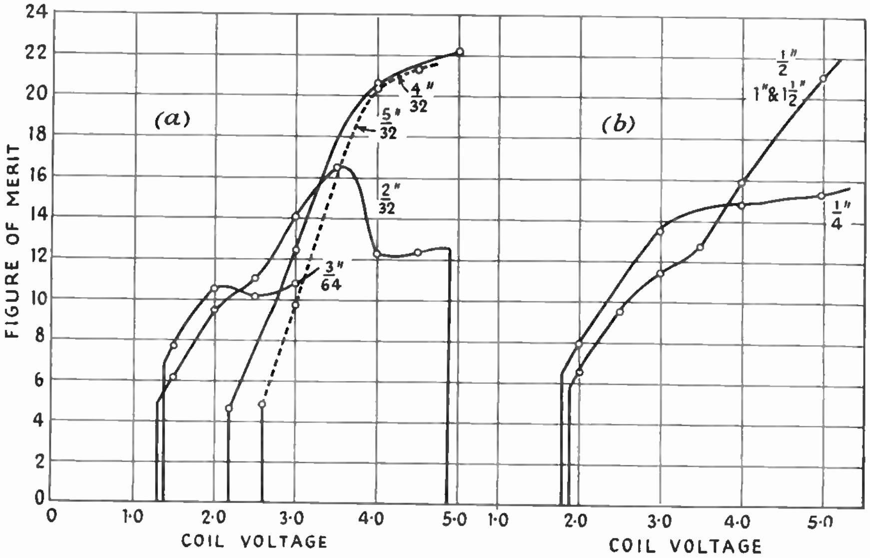


Fig. 7. Effect of strip width and strip length on figure of merit of strips of JZ alloy 8 microns thick used in a coil at 1·5 Mc/s.
(*a*) Effect of strip width at constant length of ½ in.
(*b*) Effect of strip length at constant width of 3/32 in.

explore the effect of core geometry was carried out on JZ material. Strips of the cold rolled material were cut to the desired size and then annealed in a hydrogen atmosphere at 1050°C for about three hours. The standard test coil had an air cored inductance of 0·47 microhenries and a Q of 17 at 1·5 Mc/s; the inductance voltage characteristic of this coil, with various magnetic strip cores, was measured on a high frequency bridge.

Tests on strip cores of various lengths and widths (see Fig. 7) show that there was negligible gain in inductance with strips longer than 1 in. Strips shorter than 1 in. exhibit gradually decreasing inductance but increasing Q. The inductance decrease is due to the lower effective permeability of the shorter strips (larger demagnetizing field) and this also reduces the eddy-current loss and increases the Q. Also there is less metal present with the shorter strips and so the loss is proportionately less.

These two effects tend to cancel out with the result that the figure of merit varies very little with length over most of the range. For low voltages the ¼ in. strip is slightly superior but at higher voltages the larger strips are better.

The effect of strip width is much more pronounced. Measurements were made on specimens of JZ mu-metal ½ in. long and varying in width from 1/64 in. to 10/64 in. Bistability was impossible with strips 1/64 in. and 2/64 in. wide, giving a figure of merit of zero, but for the wider strips the peak figure of merit increases with strip width. There is very slight difference between 8/64 in. and 10/64 in. wide strips indicating that this is somewhere near the optimum width. The improvement obtained with wider strips is due to the larger cross-sectional area allowing more flux to flow through the core. The demagnetizing field also increases with strip width but the increase is insufficient to counteract the effect of increased cross-sectional area.

The high F number and figure of merit obtained with the 10/64 in. wide strip suggested that it would be usable at higher frequencies so its characteristics were measured in another coil, at 2·5 Mc/s. The results (Fig. 8) show a maximum F number of 1·1 and a figure of merit of 9·6. Thus bistability is theoretically just possible at 2·5 Mc/s and this would appear to be the highest frequency at which this size strip could be used.

In testing the strip cores it was inevitable that a certain amount of manual handling took place so it was desirable to make some tests of the effect of strain on the core. A strip of

JZ mu-metal $\frac{1}{2}$ in. × 3/64 in. × 8μ was carefully annealed and then its properties were measured as it was progressively strained. The straining took the form of bending round rods of progressively smaller diameters and then straightening the specimen and inserting in the test coil. The results of some of these measurements are shown in Fig. 9. Surprisingly there is very little difference in F number or figure of merit between the unstrained specimen and one which had been strained beyond its yield point by bending round a rod of 3/16 in. diameter. The peak inductance is considerably reduced as would be expected but in the region of peak inductance the F number is always less than unity so this reduction is unimportant. Beyond peak inductance, the rate of change of inductance with voltage is virtually the same for the strained or unstrained specimens and the Q curves are similar so F and FQ are also similar. The strained specimen, in fact, gives slightly higher values of FQ so the manual handling which occurs during testing normal specimens may even be advantageous for our purpose although the effect is only small.

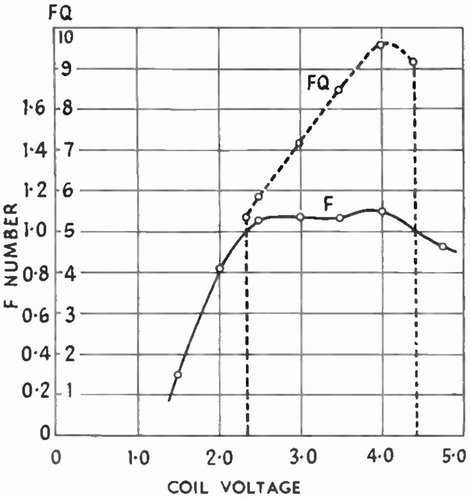


Fig. 8. Curves of "F" and "FQ" at 2·5 Mc/s for coil with core of JZ alloy, $\frac{1}{2}$ in. × 5/32 in. × 8 microns.

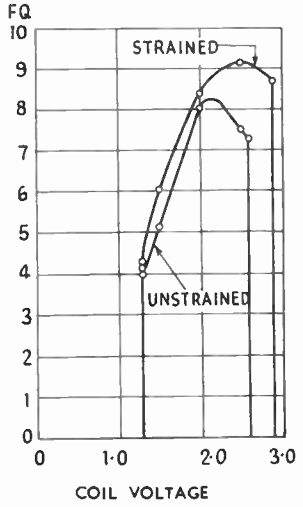


Fig. 9. Effect of mechanical strain on core of JZ alloy, measured at 1·5 Mc/s.

Eddy-currents can in principle be reduced by rolling thinner strip, but when they have been reduced there remains the problem of hysteresis loss. When the material is subjected to an alternating magnetization of such intensity that much of the time is spent in saturation, the full hysteresis loop is naturally traced out during each cycle with the result that hysteresis loss is added to the small-signal losses such as are measured on a bridge and shown in Fig. 6 (*b*). Apart from the effect on the Q, excessive hysteresis loss tends to raise core temperature, though the thin metal strip is much better cooled than is a comparatively thick specimen of ferrite which, moreover, is a poor conductor of heat. It was from this point of view that the FO alloy was designed: since there are limits to the extent to which the *width* of the hysteresis loop (coercivity) can be reduced, the height of the loop (B_{max}) was to be reduced by reducing the saturation intensity, and this was effected by bringing the Curie point nearer the working temperature.

Since the eddy-currents were still a major source of loss, the reduction of B_{max} did not have a conspicuous effect on the Q of the core. But the limitation of maximum flux is also advantageous because it reduces the operating power level. The problem of power level can be understood most simply by supposing a given coil and core to be operated over a wide range of frequencies. Then saturation of the core demands a certain value of current in the coil, regardless of frequency, and the coil voltage ωLi must increase with frequency. Alternatively, one can say that magnetic field *energy* $\frac{1}{2}(BH)_{sat}$ per unit volume of core must be transferred to and from the core *every cycle*, and therefore the *power* is proportional to frequency. In addition the tendency for the apparent permeability of the core to decrease also increases the coil power with rising frequency. In consequence attempts to use JZ material in a ferroresonant circuit at 2 Mc/s led to overheating the coil, while FO could be used safely because of its lower value of $(BH)_{\text{sat}}$.

Although one would hope to reduce coil energy a little more by increasing the amount of iron in the core, Fig. 6 (*a*) shows that at 5 Mc/s the inductance is increased five times by the iron, which suggests that only one-fifth of the flux is carried by the air core. It seems, therefore, that not much more is to be gained in this way.

Trial in a resonant circuit confirmed that temperature-rise, both of the core and of the coil, was the limiting factor in the use of these metal strips. With JZ alloy at a frequency of 1·6 Mc/s it was possible initially to get bistable operation with voltages of 38 "on" and 7·5 "off," but at such voltages the coil itself became unduly hot owing to copper loss and the overall temperature rise caused the magnetic properties of the core to change. With FO alloy saturation was attained at a much lower voltage, a typical bistable condition being 7·6 or 3·6 volts, but there was still some temperature rise and the low Curie point of the FO alloy made it more susceptible to temperature change. After a quarter of an hour in the "on" condition, the circuit was no longer bistable.

It may be asked whether some improvement could be obtained by designing the coil for less copper loss—the *Q* of the test coil alone was only 23 at 1·5 Mc/s. But the small-signal *Q* of the coil with FO core was down to 2·2 at 1·5 Mc/s, so that core loss was dominant. With FO the small-signal *Q* at 1·5 Mc/s was around 1·9 only. Some improvement might be obtained by more careful annealing and handling of the cores, and by introducing cooling arrangements: but in the present state of the art it looks difficult to exceed a carrier frequency of 1 Mc/s.

4. Practical Ferroresonant Circuits[6,7]

4.1. *Triggering*

Referring to Fig. 10 we see that the parallel ferroresonant circuit can be stable with two different amplitudes of alternating voltage across it. These amplitudes are indicated by points 1 and 2. If the circuit is in the state represented by point 1, the dissonant state, it can be triggered into the state represented by point 2, the resonant state, by applying a steady saturating field to the core for a short time. This effectively moves the inductance characteristic (b) downwards (to b′) until it intersects the circuit curve (a) in only one point. This point (2′) is then the only state point and the alternating voltage across the circuit will then build up to this value and on removal of the saturating field it will increase slightly more (to point 2) and the circuit is then in the resonant state. The time for build up is usually four or five cycles of the supply frequency but it depends somewhat on the size of the saturating or trigger pulse and on the *Q* of the ferroresonant circuit.

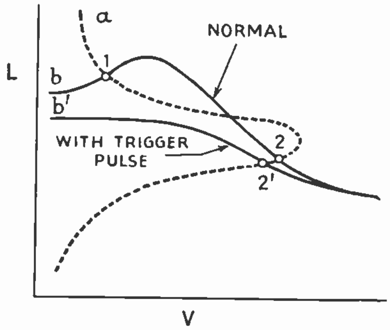


Fig. 10. The mechanism of triggering a ferroresonant circuit from small-amplitude to large-amplitude state.

The trigger field can be applied by putting another winding on the core and feeding it with direct current pulses. A single winding would require either a high impedance pulse source or else high frequency chokes or resistors in series, to prevent r.f. power being absorbed from the main winding.

A better method is to use two strips of core material with an identical trigger winding on each and then put the main winding round both. The two trigger windings are connected in phase opposition to eliminate mutual inductance between them and the main winding. The impedance of the trigger pulse source is then unimportant provided that sufficient current can be passed through the trigger winding. This method of connection also reduces the triggering power required because the two strips with the two windings are side by side and producing fields in opposite directions so that there is a good magnetic circuit with only a small air gap: see Fig. 11.

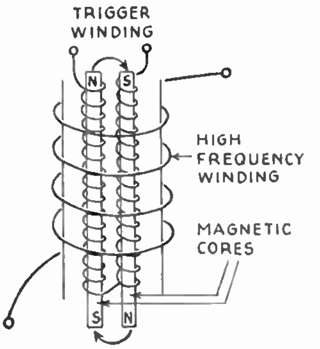


Fig. 11. Construction of ferroresonant inductor with balanced trigger windings.

To return the circuit to the dissonant state it is necessary to arrange that the two curves of Fig. 8 again only intersect in one point, this time in the low voltage region. This can be done by: (*a*) reducing the supply current which will reduce the size of the resonance curve, or (*b*) reducing the *Q* of the circuit by clamping it, or (*c*) moving the whole resonance curve downwards by increasing the circuit capacitance. Method (*b*) is usually the most convenient because the clamping can be achieved quite simply with a low impedance pulse generator and also the transition can take place within half a cycle of the supply frequency. A suitable circuit is shown in Fig. 12.

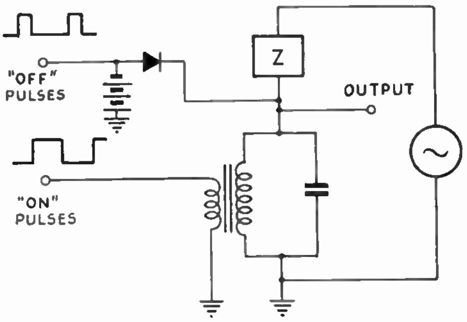


Fig. 12. Circuit for quenching and triggering a ferroresonant circuit.

Another technique which is suitable for counting or frequency dividing applications is to use two identical parallel ferroresonant circuits in series and feed them with a constant voltage high frequency supply (see Fig. 13). The two trigger windings are connected in series and the output is taken across one of the circuits. The voltage source is of such an amplitude that one and only one of the circuits can be resonant at any time. Now if a series of current pulses of suitable size and shape is fed to the trigger windings each pulse will cause the dissonant circuit to become resonant and hence the resonant circuit must become dissonant. Thus we have a simple binary counter.

This mode of operation occurs because when one core is saturated further current through its trigger winding makes little difference, whereas current through the trigger winding of the dissonant circuit saturates the core and forces the amplitude of the high frequency voltage across it to increase. This must be accompanied by a decrease in voltage across the resonant circuit because the vector sum of the two must remain constant and equal to the supply voltage. If the trigger pulse is then removed at the correct instant these trends will be continued and the states of the circuits will be interchanged. The next pulse will reverse this procedure. This circuit is fairly critical to pulse width and amplitude but it has the advantage that it can count randomly spaced pulses.

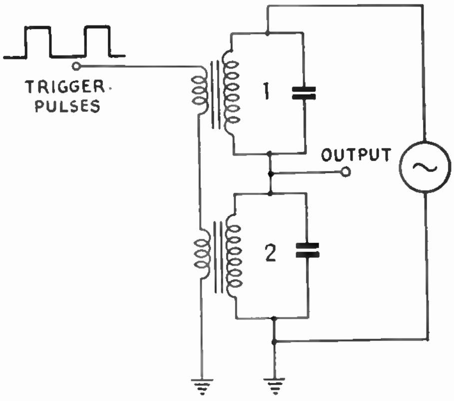


Fig. 13. Two ferroresonant circuits in a mutually exclusive arrangement.

4.2. *Shift Registers and other Computing Circuits*

For many computing applications modifications of the circuit of Fig. 12 are suitable as operations occur at fixed intervals and regular "clock" pulses are usually available.

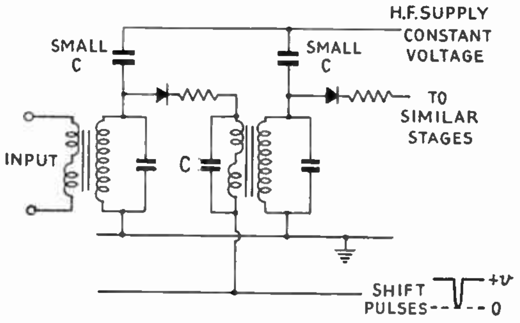


Fig. 14. A ferroresonant shift register.

Figure 14 shows the circuit of a shift register where the output of one circuit is used to trigger the succeeding one[8]. If an input pulse is fed to the trigger winding of the first circuit, causing it to go into resonance, the following shift pulse will cause the diode to conduct and this will load the circuit sufficiently to return it to dissonance. At the same time it charges the capacitor C and at the end of the shift pulse this capacitor discharges through the trigger winding of the second stage and forces it into resonance. Various logical circuits can be built in a similar way by interconnecting units and by having more than one input to a trigger winding. For instance, Fig. 15 shows a three-stage binary counter requiring no shift pulse and Fig. 16 shows a two-input logical adder.

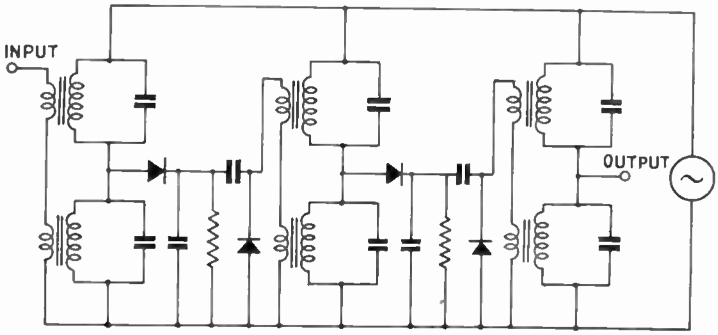


Fig. 15. A three-stage binary counter.

Thus ferroresonant circuits can perform any of the functions required in a digital computer. Their maximum operating speed is in the region of 100 kc/s pulse rates at present, but this may be increased if more suitable core materials can be found.

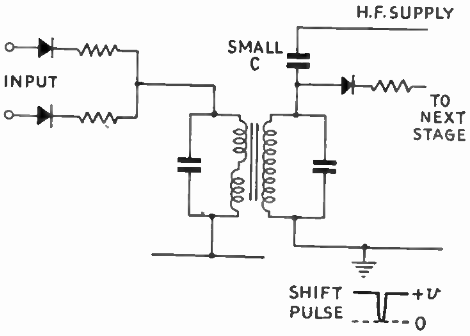


Fig. 16. A two-input logical adder.

5. Acknowledgments

The work on which this paper is based was carried out in the Electrical Engineering Department, University of Birmingham, and it was supported by a Ministry of Supply Research Contract. The authors wish to record their gratitude to the Computer Components Committee of the Ministry of Supply, to the Signals Research and Development Establishment, Christchurch, and to the Post Office Research Station for their assistance in providing the information and materials which made this work possible.

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DISCUSSION ON
"High Speed Analogue-to-Digital Converters"

F. Beckett†: I feel that there is an error in the quoted accuracy required for the various summing resistors (Section 4.2.4.) This reads:

"For an accuracy of conversion of 0·1 per cent. of full scale, the requirement for accuracy of the switched summing resistors in order of decreasing significance is 0·1%, 0·2%, 0·4% and so on."

An error of 0·1% in the most significant place would produce an output error of 0·05% and an error of 0·2% in the next place would also produce an output error of 0·05%, and so on for all 10 digits. These errors may be cumulative giving a total error of 0·5%.

An accuracy of 0·1% on all ten resistors would give a total error of 0·1% but this would not be a practical solution, and some compromise seems called for, for example, 0·05% for the most significant, 0·07% for the next, 0·1% for the third, 0·14% for the fourth and so on giving a maximum error of about ·08% for the output.

The stability test discussed in Section 4.4 while being a very effective single checking procedure, is only checking errors in the most significant place and the combined error of the other nine places. The individual errors may of course cancel out in this case but still be significant in other combinations.

G. J. Herring and D. Lamb (*in reply*): Mr. Beckett's first point, regarding cumulative errors, is certainly correct in principle. It is evident from re-reading the salient paragraph in the paper that the wording does not quite convey the sense intended. The purpose of the sentence was to point out that the accuracy required of the resistors decreases with the significance of the digit concerned. Thus for an accuracy of conversion of 0·1% of full scale, the requirement for accuracy of the switched summing resistors, taken separately in order of decreasing significance, would be 0·1%, 0·2%, 0·4% and so on. If errors of this magnitude were allowed and were of the same sign, then the total error in the output would be 0·1% for each conducting resistor and 0% for each earthed resistor. In this particular converter the values of the five most significant resistors were made to be as accurate as possible, the next three had a relaxed accuracy requirement and the remainder were selected from the 5% preferred value range. This arrangement is less logical than the $\sqrt{2}$ sequence suggested by Mr. Beckett, but was chosen so as to allow as much tolerance as possible on the very large valued resistors associated with the least significant digits, as these are the least stable. It is worth noting that the probability of errors being additive is small (it is usually neglected in analogue computer work, because checking procedures will show it up if it should occur), and that the probability of only half the resistors being in the conducting state at any one time is considerably greater than that for any other combination.

Since the paper was written, full tests on the converter have been completed. There is one point at which the error is 120 mV; over the rest of the input range of ± 100 V the accuracy is better than this.

The stability test quoted in section 4.4 checks rather more than errors in the most significant place and those in the other 10 places combined. It is also a test of the drift in the d.c. amplifier and reference supplies, which shows up as an overall shift in the voltage level. Drift in one of the digits (due, say, to one of the resistors changing, or a switch becoming unbalanced) causes a change in one level relative to another. It is true that changes may cancel and thus not be shown up by this test, but cancellation to better than 0·1 per cent. of full scale is considered to be unlikely, and such faults would in any case be found in a check on the accuracy of individual digits. Both these tests would probably be included in a routine checking procedure.

It may be of interest that the converter has now been used to digitize a number of input voltage waveforms, including random functions, and that preparations for connecting the converter output direct to a Pegasus digital computer are nearly complete.

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* G. J. Herring and D. Lamb, *J.Brit.I.R.E.*, 17, pp. 407-420, August 1957.

† Received 21st September 1957. Mr. Beckett is with Ericsson Telephones Ltd.

U.D.C. No. 681.14.

# of current interest . . .

Formation of International Federation of Control

At a meeting in Paris last September attended by representatives of 19 countries, the International Federation of Automatic Control was set up as a functioning body. Its objects are to sponsor international congresses and promote interchange of information on control activities. Engineers in Great Britain were represented through the British Conference on Automation and Computation.

The Federation defined "automatic control" in its constitution as "deemed to cover the field of open and closed loop (feedback) control of physical systems (including servomechanisms, instrumentation, data processing, and computers when part of control systems) in theoretical and applied aspects."

Moscow will be the site of the Federation's first congress, which will be held in June or July of 1959 or 1960. The meetings will probably take place at the University of Moscow, and the topics will be comprehensive and will include theoretical as well as practical applications of the science of control.

Other accomplishments by this IFAC General Assembly included plans for: a series of smaller, highly specialized meetings, in response to suggestions that the Federation start some projects before 1959, and the preparation of an international directory of leading control engineers and their work in all countries.

Independent Television in the North East

The Independent Television Authority has recently announced that the station which is to transmit its programmes in the North East of England will be built at Burnhope, about five miles south-east of Consett, Co. Durham. It is hoped to open the service late next year.

The coverage of the station is predicted as a rough crescent running from Alnwick in the north, through Middleton in Teesdale in the east, and nearly to Whitby in the south. The highly concentrated populations of Newcastle, Sunderland, Middlesborough and South Shields will all lie well within the service area. The Burnhope station will have an effective radiated power of about 100 kilowatts and a 750 foot mast will be used.

B.B.C. Experimental Colour Television Transmissions

On October 7th last the B.B.C. started a new series of experimental transmissions to assist the Television Advisory Committee in its report to the Postmaster-General on colour television.

The purpose of this latest series of tests is:

(1) To provide a source of high-grade colour picture signals so as to permit colour receiver development work to continue.

(2) To enable further experience to be gained in the operation of the colour studio and colour television equipment.

(3) To obtain further knowledge of the compatibility provided by the particular system of colour transmission being tested, which has been developed from the system used for public transmissions in the U.S.A. (the N.T.S.C. system).

This new series of experimental transmissions, which will take place outside normal programme times and continue for about six months, will be transmitted from the Crystal Palace station on Channel 1. The transmitted material will include live studio productions and films and slides from a colour television studio and control room at Alexandra Palace.

The B.B.C.'s Director of Engineering, Sir Harold Bishop, said in a recent broadcast that the results of experiments so far were encouraging and seemed to show that the N.T.S.C. system had great possibilities. A lot had still to be done to develop terminal apparatus both at the transmitting and at the receiving ends. In the studio, the colour camera must be simplified and made more reliable and easier to set up and operate. He hoped, for example, that in due course a single picture-tube would do the job of the three now used.

There were about forty-two valves in the present experimental colour receiving sets compared with some twenty in a black-and-white set. There must obviously be some simplification here to cut cost and improve reliability. A colour projection tube giving a picture on the wall of the living room comparable in size and quality to the best type of home cine projectors might be a possible line of development, Sir Harold suggested.

THE APPLICATION OF ANALOGUE COMPUTER TECHNIQUES TO THE DESIGN OF AERO ENGINE CONTROL SYSTEMS*

by

A. D. Jeffery (Associate Member)†, J. M. Dempsey†,
H. Saville, B.Sc.(Eng.)‡ and K. Gill, B.Sc. (Eng.)‡

A paper presented at the Convention on "Electronics in Automation" in Cambridge on 29th June 1957. In the Chair : Professor D. G. Tucker (Member).

SUMMARY

The problem of aero engine control systems is shown to have reached the degree of complexity at the present time that makes it necessary to embark on analogue methods of simulation in order to predict the behaviour of the system. The parameters to be controlled are discussed and the way in which interaction may affect the individual loops is explained together with a review of the requirements of a control system from the pilot's handling, and the performance view points. As illustrations, examples of control system functional components are used to illustrate the methods of adaptation of a practical hydraulic system to analogue methods. The use of the computer results is discussed in formulating an optimum system design.

1. Introduction

When the gas turbine engine was introduced into Service use in the Meteor and Vampire aircraft about 12 or 13 years ago the control systems used largely fulfilled the promise of early writers that the complication of the highly developed piston engine carburettor or fuel injection system could be left behind. In their place we were to be blessed with simple systems involving only a pump, throttle valve and means of altitude compensation. No longer would it be necessary to worry about such things as mixture strength, boost controls, fuel enrichment over-rides, etc. This was, of course, true in those days when piston engines were stretched to the limits to produce the performance demanded and when the thrusts of early jet engines gave such big improvements in aircraft performance that the engine performance was no longer a limiting factor and the engine control requirements could easily be met by the simpler system.

The first systems used, known as the Barometric Pressure Control or B.P.C. system were only suitable for very limited applications and were soon replaced by "flow scheduling" systems. The B.P.C. system delivered fuel to the engine at a controlled pressure. Since the flow was a function of this pressure, the flow requirements could be matched to this controlled pressure to schedule the flow under any flight conditions. Inaccuracies at altitude with this system have made it only suitable for very limited uses. Hence the flow scheduling system was introduced.

In the flow scheduling system, the fuel required for any flight condition is metered to a value which is calculated from the known engine performance data as for the B.P.C. system, but the fuel is measured by means of a pressure drop across a metering orifice of known area.

The parameters used for metering the fuel flow in both systems were the throttle position and the atmospheric ram pressure. This ram pressure is the total head pressure due to aircraft altitude and forward speed and therefore is sensitive to these two main operating variables of the aircraft in flight. Only the variation of atmospheric temperature is then not accounted for in the schedule system.

It can be seen in Fig. 1 that a scheduling system based on the ram pressure can only give

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‡ Armstrong Siddeley Motors Ltd., Coventry.

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an approximately correct fuel flow over the complete flight speed range of the aircraft. For aircraft of several years ago this variation only amounted to an error of about ± 1 per cent. on engine speed when temperature variations about standard atmospheric conditions were neglected.

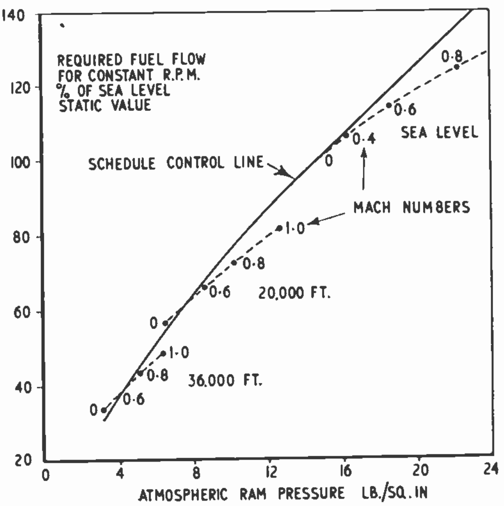

Fig. 1. Fuel flow as a function of ram pressure for a schedule system.

However as speed ranges have increased in recent years this scheduling inaccuracy has widened until it is now completely impracticable to use a single pressure parameter to schedule the fuel. For instance, the total variation of engine speed for an aircraft capable of sonic speeds at sea-level, when temperature variations from arctic to tropical have to be considered as well, may amount to ±400 rev/min. on an engine datum speed of 8000 rev/min.

Those who would prolong the use of scheduling systems have devised methods of correction to maintain a certain amount of compensation and so the fuel system has grown like a Christmas tree with possible additions such as air temperature corrections, augmentor valves, pressure potentiometer devices etc., until we are now in danger of arriving at systems which are equal in complexity to the piston-engine carburettor system.

The advent of high supersonic speeds has now made accurate scheduling extremely difficult and it has therefore become clear that a new approach based on closed loop, or governing systems instead of the open loop or scheduling system has become necessary.

Speed governors have been used on aero engines in the past but they have taken the form of top speed limiting devices and have not been the primary functional element of the control system. As a result the governor has taken the second place in design and its development has not kept pace with the requirements.

These comments relate to pure jet engines. In the case of propeller turbine engines, development has followed slightly different lines, since a further variable is available, namely propeller pitch. Thus the fuel flow can control engine power supply while the propeller pitch can be used to control the power loading. Hence the engine speed can be chosen to give optimum efficiency conditions. The development of propeller control systems for piston engines was readily adapted to turbine engines and used for governing the speed while the fuel flow remained basically a scheduling system.

Such governing systems which have been attempted for pure jet engines have been developed by trial and error design and adjustment with only limited consideration given to the theory of stability. The variations possible in arriving at a satisfactory system resulted in many wrong lines of approach being tried without success.

This trial and error method would eventually provide satisfactory test-bed running, but then in flight testing much the same procedure had to be adopted. The possibilities of this method together with the use of intuitive knowledge gained by people with years of practical experience, however, should not be relied upon completely in the unknown realms of supersonic flight, where the slightest suggestion of instability in some control loop may prove disastrous.

It is therefore clear that only a full theoretical approach with practical design considerations linked at the outset will now suffice for future aero engine control systems.

If we now accept that this approach is necessary the methods of carrying this out must be considered. Full mathematical methods are available and are well known so far as analysis of linear systems are concerned. In addition, methods have been developed by which non-linearities may be introduced.

The calculation, however, is an extremely long and tedious process particularly when building up a control system where many possibilities may require separate investigation. The arithmetical work may, of course, be considerably eased by application of digital computer techniques. This method however can carry out no further work than could in principle be done by manual methods, the only saving is in time.

In a digital machine, the numerical value of a quantity is directly represented by a train of electrical pulses following each other in time sequence. Each pulse represents a digit (generally in the binary scale for ease of manipulation) and each train of pulses, known as a "word," represents a number on which arithmetic operations are to be performed. Since a word generally consists of a large number of digits a very high degree of accuracy may be obtained: for example, if a change is made in the least significant digit of a binary number of, say, fourteen digits, the change produced is one part in 2^{14}, i.e. one part in 16,384. The arithmetic operations performed on the numbers within a digital computer take place at very high speed, of the order of milliseconds, so that where many calculations have to be carried out on large quantities of similar data, a digital computer has obvious advantages.

Information is generally fed into a digital computer by means of punched tape and the output is produced in the form of typewritten sheets of numbers or as a punched tape. If the results of a computation are required in the form of graphs, for instance, these would have to be plotted manually or additional equipment would be required involving the expenditure of larger sums of money than the £20,000 to £50,000 required for a basic digital installation.

Fortunately the results required by a control engineer are not wanted in highly accurate mathematical form but more in a qualitative pictorial form. This being so, a method of solution where the results are presented on an oscilloscope in the form of a continuous function of time provides the ideal form of solution. In this way the results appear directly in the form that would be seen by an observer watching the actual machinery being controlled.

The apparatus to produce results in this form is the analogue computer. It will be seen later that this machine may be used to incorporate the non-linear effects met in practical systems; that it may simulate completely in an electrical form the exact behaviour of a mechanical system; or when the system becomes more complex and when individual components have been investigated separately it may be used to solve the combined simultaneous differential equations representing the transient behaviour of the complete system.

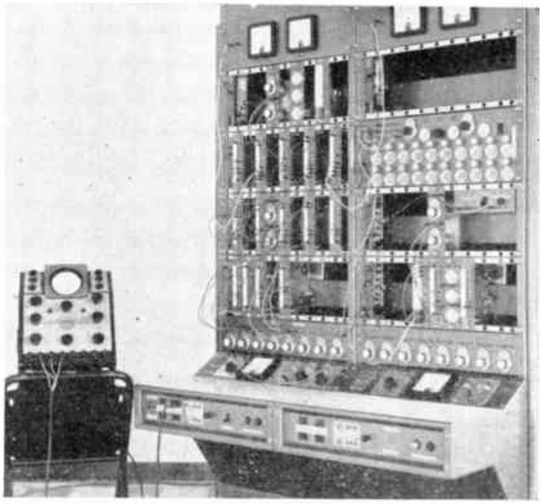

Fig. 2. Analogue computer for aero engine control problems.

In an analogue machine, a quantity is represented by a voltage on some suitable scale. The voltages are therefore true analogues of the variables under consideration and not a numerical representation digit by digit. The basic computing element is the d.c. amplifier which can be set up to perform summation, integration, differentiation etc. By the inclusion of further units, non-linear relationships can also be studied. An analogue computer result is obtained in the form of a voltage varying with time. This can be measured on a cathode-ray oscilloscope or plotted in graphical form using a pen recorder. Consequently, the accuracy of the results is generally not greater than 0·5 to 1·0 per cent. of the full-scale value unless special precautions are taken, which may require more expensive equipment than the £3,000 to £15,000 needed for a general purpose machine.

Figure 2 shows a typical analogue computer set up to investigate the problem given later in this paper.

One of the advantages of an analogue computer lies in its ability to be a small machine for small problems and to be easily extended to deal with more complex problems. As the results are produced instantaneously on switching on, the machine enables the engineer to set up a model of his system and to study the effects of including or excluding certain portions and, after observing the results, to make changes in the most suitable parameters and to see immediately their effects.

A further advantage of an analogue computer is that it can be operated in real time, that is, the variables in the machine change at the same rate as the variable in the problem. As a result the machine can be used to simulate part of a system under design and can be operated with existing machinery to determine their combined performance.

There is a danger when considering the applications of analogue computers in attempting to simulate too big a problem at once. One should not depart too radically from a parallel theoretical consideration of the problem and the methods described in this paper provide a means of making a step-by-step attack on complicated control problems without losing an understanding of the order of the results to be expected and at the same time making the most economical use of computing equipment.

It is difficult to generalize on the amount of equipment necessary for any type of problem, but from experience gained on the problems of aero engine control, it does appear that complicated computer "set-ups" become unwieldy. It is thought that the simplifying techniques explained later will enable most problems to be reduced to a practical size. Additional space, however, must be available on the computer for the non-linear elements, multipliers, etc., when required.

In conclusion, a digital machine provides very accurate results at high speed but is generally only economic if used for large numbers of calculations and where numerical answers are required. An analogue machine is more suitable for less accurate work where immediate flexibility in operation and real-time working are useful and where graphical results are required.

2. Requirements of Aero Engine Control Systems

It is proposed now to discuss the many requirements that have to be satisfied by an aero engine control system.

These differ to some extent according to the application of the engine. For instance, an engine in a fighter aircraft will be handled much more roughly than in a bomber or passenger transport aircraft. On the other hand, the accuracy of control of an engine in a transport aircraft will require to be higher, in order that the engine may be left to continue to run at its most economical condition for long periods without attention by the flight engineer.

These differences are mainly in degree and in any case it is necessary to have a control system which will allow the engine to respond rapidly to throttle movements, be able to limit over-shoots and oscillation, have a high degree of accuracy over a wide range of operating conditions, and prevent engine damage due to stalling, combustion blow-out, exceeding the limiting engine speed, or exceeding limiting engine temperatures. In addition the system requires to be compact, designed to very strict weight requirements, and have safety features to prevent engine damage in the event of any failure of the control.

Considering these points we find that the first four relating to response, overshoot, damping, and accuracy are all concerned with the dynamic characteristics of the system and the engine, and it is these that have to be determined by an analysis of the system.

So far as speed control is concerned, the target should be to produce stable governing systems with an accuracy of not less than ±20 rev/min. in 8000 rev/min. and with overshoots on acceleration of not more than 100 rev/min. Damping should be such that the oscillation virtually disappears within 2 cycles.

Additional controlling requirements which will produce closed loops interacting on the main speed governing loop are required for jet pipe temperature control, variable nozzle controls, reheat controls, and variable intake controls. Any of these may be required on a given engine installation depending on the aircraft application, and in a full study the interaction of the closed loop would require investigation.

However, the principal loop and the one requiring highest performance on an engine installation is the speed governor and this will be considered further in the following sections.

3. Control System Development Using Computer Techniques

The system to be analysed here by way of example is one which does not exist in its entirety on any present engine but it is hoped by means of the example to show how the control system design can be developed along lines which will provide the optimum operation for a given application.

We shall assume that initial discussion between the engine and accessory manufacturers have suggested a system based on a variable displacement piston type pump and an altitude corrected flow control. The pump is engine driven and its displacement is varied by means of a servo-operated piston controlled by the flow control signal. The flow control measures the fuel flow as a pressure drop across a restrictor and this pressure drop is compared with a selected pressure drop and the error signal used to control the pump servo piston. It can be seen now that if we control the restrictor size by means of an altitude control, and the selected pressure drop by means of the pilot's throttle, we have a simple "schedule system" described earlier. This principle uses the well-known hydraulic equation for turbulent flow through a restrictor where flow is proportional to the restrictor size and the square root of the pressure drop across it.

In our example we propose to retain the altitude control but to vary the selected pressure drop, and therefore the fuel flow by means of an engine speed error sensing device. This then controls the fuel flow to maintain a governed engine speed and we have replaced the scheduling system by a speed-controlled closed loop system.

This system can then be represented in block diagram form as shown in Fig. 3, where it can be seen that the main loop (shown in double lines), has two subsidiary loops.

It should be noted that the retaining of the altitude corrected flow control when "closing the loop" has two advantages. In the first place, as the aircraft is flown to high altitude, the range of fuel flow allowed by the fuel system from idling to full throttle is considerably reduced. Secondly as the "gain of the engine (rev/min. change for fuel flow change) increases with altitude, the gain of the fuel system (fuel flow change for rev/min. change on governor) is reduced by the altitude control, so maintaining approximately constant "loop gain."

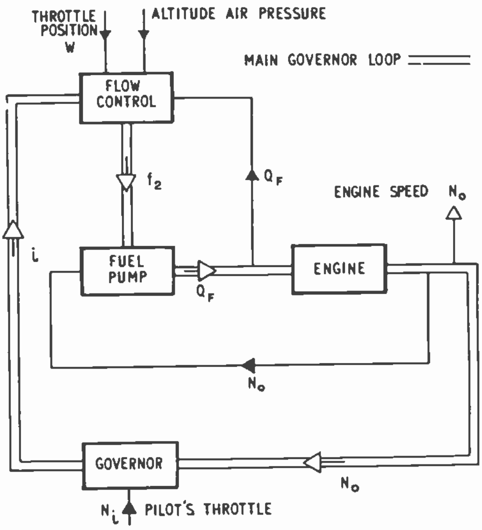

Fig. 3. Block diagram of engine control problem.

In our example, with the altitude control retained we would expect that on open loop, or scheduling control, we would have a possible engine speed variation of, say, ±400 rev/min. about a datum and our aim is to reduce this wander to less than ±20 rev/min. It is necessary to restrict overshoots and to achieve change in selected datum in the minimum possible time. For the purpose of illustration of the techniques to be adopted, we shall neglect the special requirements of acceleration control, idling datum shift, jet pipe temperature control etc. and investigate solely the behaviour of the loop shown in Fig. 3.

3.1. *Linearized Analysis of Proposed System Components*

3.1.1. Flow control and pump

In order to establish the complete transfer function for the flow control and pump system it is necessary to have a preliminary idea of the type of system envisaged. In our example this is taken to be of the form shown in Fig. 4 which shows how the pump displacement lever is moved by the control valve f_2 through a hydraulic amplifier. This valve f_2 is moved by the flow control to establish a balance between the pressure drop across the restrictor f_E and the load applied by the throttle lever W. Restrictors f_3 and f_4 represent the fluid friction in the pipe lines to the diaphragm chamber when movement is taking place following a disturbance.

It should be noted that this is the basic concept of the devised system; deviations in performance and their effects will be considered later when the initial design analysis of the whole loop has been carried out.

We shall now establish the individual transfer functions for the pump and flow control showing the response of the fuel flow change to a change in throttle position W. Modifications will be made later to show how the speed signal is to be introduced to the flow control.

To simplify the mechanism of analysis we will assume that Δ implies the total small variation of any parameter about a datum value. At this stage it is implied that the analysis to follow is linearized and Nyquist criterion for stability would be used to estimate the system performance if analogue techniques were not used.

The pump and flow control are considered separately as follows:

(*a*) *Pump (fixed speed)*

The flow equation for an incompressible fluid flowing through a restriction is

$Q = f\sqrt{(\delta P)}$ (gallons per hour say)

The linearization of this type of equation can be achieved in many ways, but for simplicity we shall take logarithms and differentiate. The quantities and suffices are as defined in Fig. 4 and it is noted that

Q = fuel flow
P = fuel pressure
f = flow number, which is a function of restriction area, coefficient of discharge, and fluid density
A = area
R = spring rate

The suffix "0" implies initial or datum conditions.

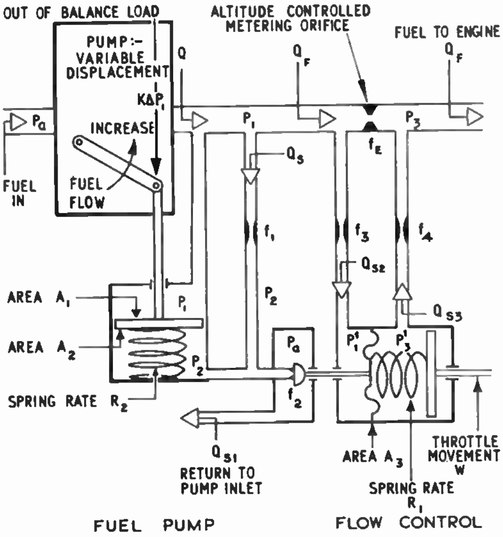

Fig. 4. Schematic diagram of the pump and flow control system.

For flow in restrictor f_2,

$$Q_{S1} = f_2\sqrt{(P_2 - P_a)}$$

Then
$$\frac{\Delta Q_{S1}}{Q_{S10}} = \frac{\Delta f_2}{f_{20}} + \frac{\Delta(P_2 - P_a)}{2(P_2 - P_a)_0}$$

i.e. $$\Delta Q_{S1} = \left(\frac{Q_{S1}}{f_2}\right)_0 \Delta f_2 + \left(\frac{Q_{S1}}{2(P_2 - P_a)}\right)_0 \Delta P_2$$

Since in our case P_a is constant, $\Delta P_a = 0$.

Therefore $\Delta Q_{S1} = K_1\Delta f_2 + K_2\Delta P_2$ ....(1)

Similarly it can be shown that

$$\Delta Q_S = \Delta Q_{S1} + 13A_2\frac{\mathrm{d}}{\mathrm{d}t}\Delta x$$
$$= \Delta Q_{S1} + K_3\,p\Delta Q \qquad \text{.........(2)}$$

where 13 is a conversion factor and x is displacement of piston.

$$\Delta Q_S = K_4\Delta(P_1 - P_2) \qquad \text{.........(3)}$$

$$\Delta Q_F = \Delta Q_S + \Delta Q \qquad \text{.........(4)}$$

$$\Delta Q_F = \mathrm{K}_5\Delta P_1 \text{ (assuming } \Delta P_3 = 0) \qquad \text{.........(5)}$$

Consider out-of-balance loads on the pump servo piston.

$$A_1\Delta P_1 = A_2\Delta P_2 - R_2\Delta x - K\Delta P_1$$

i.e. $(A_1 + K)\Delta P_1 = A_2\Delta P_2 - R_2\Delta x$ ....(6)

where

$$K_1 = \left(\frac{Q_{s1}}{f_2}\right)_0$$

$$K_2 = \left(\frac{Q_{s1}}{2(P_2 - P_a)}\right)_0$$

$$K_3 = m.13A_2$$

$$m = \frac{\Delta x}{\Delta Q}$$

$$p = \frac{\mathrm{d}}{\mathrm{d}t}$$

$$K_4 = \left(\frac{Q_s}{2(P_1 - P_2)}\right)_0$$

All constants K_1, K_2, etc. are computed from the steady state or datum conditions. The method outlined above is condensed but shows the technique used in arriving at the pump operational equations (1) to (6), all of which have to be satisfied simultaneously when considering the performance of the system.

Combining equations (1) to (6) gives a complete pump transfer function of the form:

$$\frac{\Delta Q_F}{\Delta f_2} = \frac{-\beta_1}{1 + \tau_1 p}$$

which is a simple first-order lag with respect to the response of fuel flow Q_F to a change in valve flow number, f_2.

β_1 is the frequency invariant gain constant and τ_1 is the time constant, both of which are only constant for a given set of values of pump delivery pressure and flow datum.

(*b*) *Flow Control*

By following the same procedure we obtain the following equation giving the transfer functions for the flow control in terms of fuel flow and throttle signal

$$\beta_2\Delta Q_F - \beta_3\Delta W = (1 + \tau_2 p)\Delta f_2 \quad \text{.........(7)}$$

3.1.2. Gas turbine engine

The transfer function of the engine itself is calculated from the known aerodynamic characteristics of the engine components. In our example we will consider the engine transfer function to consist of two simple time constants and one time delay lag. The time constants represent the effects of engine rotor inertia and the inflation time of the engine air space. The time delay is an item not yet fully understood, but it has been shown by response testing to exist on some engines and it may be connected with the type of combustion chamber or fuel burning system used.

$$\frac{\Delta N}{\Delta Q_F} = \frac{K \exp(-\xi p)}{(1 + \tau_1 p)(1 + \tau_2 p)}$$

Typical values which will be used in the investigation given here representing sea-level static operation of an engine are:—

$K = 2{\cdot}5$ rev/min. per gal/hr; $\xi = 0{\cdot}10$ sec; $\tau_1 = 0{\cdot}8$ sec; $\tau_2 = 0{\cdot}05$ sec.

3.2. *Analogue Computer Analysis of System*

Having decided on the characteristics of what might be termed the invariable components of the system, namely the pump and flow control and the engine itself, we are now able to consider the type of system to be used for closing the loop and satisfying the control system operational requirements.

We are free to vary within limits the constants of the fuel system components but not the form of equations. We are given an entirely free hand however to specify the type and behaviour of additional equipment which may be added and we will therefore examine in detail some of these possibilities to show how the choice can be made.

It is necessary to review the way in which a speed governor behaves on an aero engine to appreciate the way in which engine speed may vary. (See Fig. 5.)

If we are to use a pure "scheduling system," it has been stated that we may expect a total speed variation at a fixed throttle position of ±400 rev/min. Conversely, the fuel flow required for constant speed can vary by ±160 gal/hr using the engine characteristic quoted above.

In order to provide a governing system to maintain engine speed within ±20 rev/min, a loop gain of the order of 20 is required. It will be shown, however, that this is impossible with a system using only proportional control because of instability. In practice a lower gain must be employed and means provided of eliminating the resulting change of speed or "creep" as it is known.

3.2.1. Proportional governor control

An additional valve is now to be added to the flow control so that the pressure difference appearing across the diaphragm (in Fig. 4) in the flow control may be made some variable proportion of that across the main metering orifice f_E.

Hence $(P_1' - P_3') = k(P_1 - P_3)$

Now the pump and flow control system works so that $(P_1' - P_3')$ is kept to the value selected by W and hence we can vary $(P_1 - P_3)$ and also the fuel flow, by varying the ratio k.

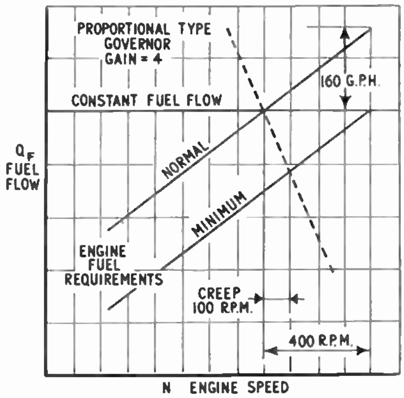

Fig. 5. Engine fuel requirements and governor rate curve.

This additional means of fuel flow control is provided by putting a fixed restrictor at f_3 and a variable restrictor f_5 as a bleed from the diaphragm chamber as shown in Fig. 6.

The operation of the flow control is now as follows. There are three means of varying the controlled fuel flow:—

(*a*) The size of the metering orifice f_E is altitude controlled and therefore provides approximately the required proportional control of fuel flow with change of height.

(*b*) The spring force is varied by the input signal W which would be linked directly to the throttle to provide schedule fuel control. The governor signal could be combined with the throttle linkage to act on the movement W but it is an advantage to separate this by the addition of the third control.

(*c*) This is the variation of the restrictor f_5 as described above. This avoids the necessity for the governor signal going through a flow control throttle servo, which necessarily would add a large time constant to the loop.

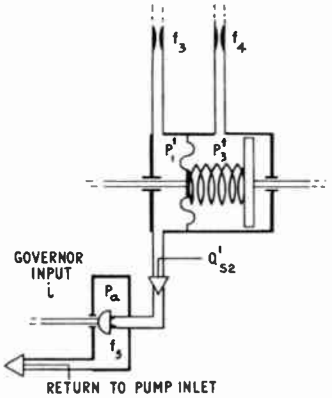

Fig. 6. Scrap view of flow control showing addition of control orifice f_5.

The equation for the flow control now needs to be modified to include the effect of this governor controlled bleed and hence a relationship is established for the response of the valve f_2 following a change of f_5.

The complete flow control equation is given by

$$\beta_2 \Delta Q_F - \beta_4 \Delta f_5 - \beta_3 \Delta W = (1 + \tau_{2p}) \Delta f_2$$

where β_2, β_3, and β_4 and τ_2 are constants for the flow control.

The pilot's throttle will control both W, which schedules a fuel flow, and the selected governor datum. Hence to obtain the full system analysis and results for a step change in throttle position both inputs ΔW and Δf_5 must be retained in this equation.

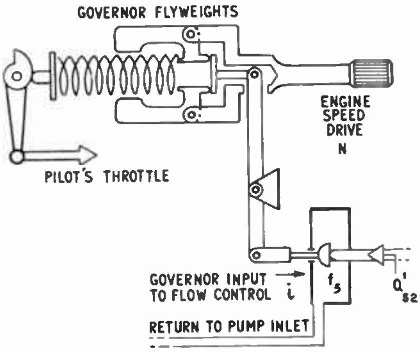

Fig. 7. Application of governor speed signal to movement of valve f_5.

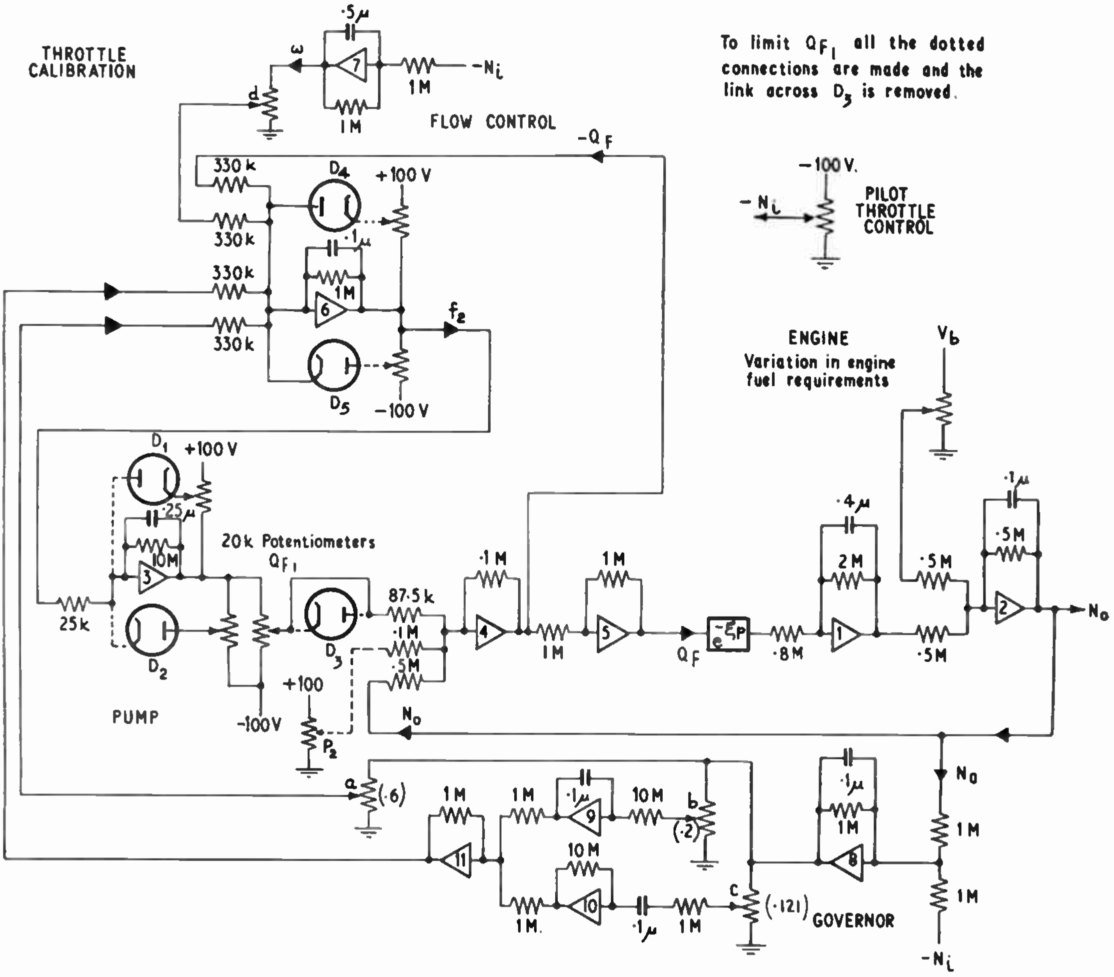

Fig. 8. Computer set-up for complete system.

Figure 7 now shows the way in which the speed error signal is applied to the valve lift through a normal governor weight and spring device driven directly from the engine. The governor datum is altered by the cam on the spring linked to the pilot's throttle and the system gain is determined by the governor spring rate.

The change in the flow number of the flow control valve f_5 is given directly by the linearized equation $f_5 = Z_1 N_e$ where N_e is the speed error.

The system is fully linearized and can be applied to the analogue computer by standard methods. Fig. 8 shows the computer set up for the complete system. When simulating a proportional governor, the coefficients "*b*" and "*c*" are zero and the limiters are out of circuit. The potentiometer "*a*" is used to represent the adjustment to loop gain provided by changing the spring rate.

Figure 9 shows the result of a step change in selected engine speed from 8000 to 8600 rev/min when the gain is adjusted to 6. The results throughout are shown for an engine operating under conditions when maximum positive errors exist. With this gain the band width of possible variation is ±70 rev/min and is not acceptable. In addition overshoot and damping are poor and additional means

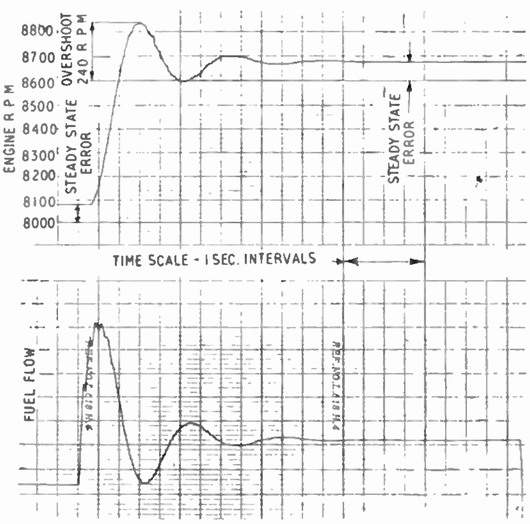

Fig. 9. Response of engine to throttle change from 8000 rev/min—8600 rev/min with proportional system. Loop gain = 6.

are required of improving these conditions. It is seen that there is an initial overshoot of 240 rev/min above the selected datum.

3.2.2. Removal of steady state error

A method of improving the accuracy of the governor other than by increasing the gain must now be found. We can accept the error for a short period of time, say 6 seconds during which time some means is needed of trimming out the error. This can be done in several ways and for our purpose here we will consider a direct approach where the error continues to be removed until the governor weights and arm have returned to a unique position. This position will only be reached when the speed error is zero.

The controlling influence of the governor on the fuel flow relies on a change in f_5. Hence some way to modify f_5 must be found in order that the governor arm may be allowed to retain its unique position with zero speed error.

This can be done as shown in Fig. 10 where f_5 has now been replaced by f_5' and f_5''. Here the valve f_5' is in parallel with a long taper needle f_5'', so that the effective flow number f_5 is now the sum of f_5' and f_5''. The position of f_5'' is controlled by a piston having a fixed pressure difference across it. A bleed hole allows fuel through the piston and out of a further variable restrictor valve controlled by the governor arm. It can be seen that the needle valve piston is stationary only when the flow through the piston restrictor f_6 equals that through f_7. With a constant pressure drop across f_5' this condition will exist when the governor arm is in its unique position.

It is noted that the system as described will wander if the supply pressure to the engine P_3 varies. Addition of a constant pressure valve across f_5' is therefore necessary.

The equation for the governor is now modified as follows:

$$\Delta f_5 = \Delta f_5' + \Delta f_5'' = Z_1 N_e + Z_2 \int f_7 \, dt$$

$$= Z_1 N_e + Z_2 \frac{N_e}{p} \quad (\text{since } f_7 \propto N_e)$$

The integrating constant Z_2 is adjusted by the dimensions of the system. On the computer set up in Fig. 8 this integration is introduced by adjustment of potentiometer "b" to give the best rate of removal of the error without too great an increase in the value of the overshoot.

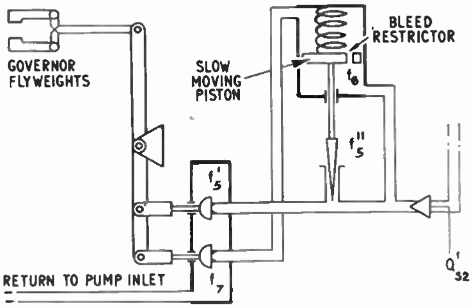

Fig. 10. Method of removing steady state error.

Figure 11 shows the results of this computer test when the integrating constant has been chosen so that the possible ±70 rev/min error can be corrected in a time of 6 seconds. It is seen now that the initial overshoot has been increased to about 400 rev/min due to the introduction of the integration.

3.2.3. Limitation of initial overshoot

The initial overshoot which is seen to be of the order of 240 rev/min on Fig. 9 and 400 rev/min on Fig. 11 requires reduction. This overshoot could be reduced by lowering the loop gain but the rate of response would

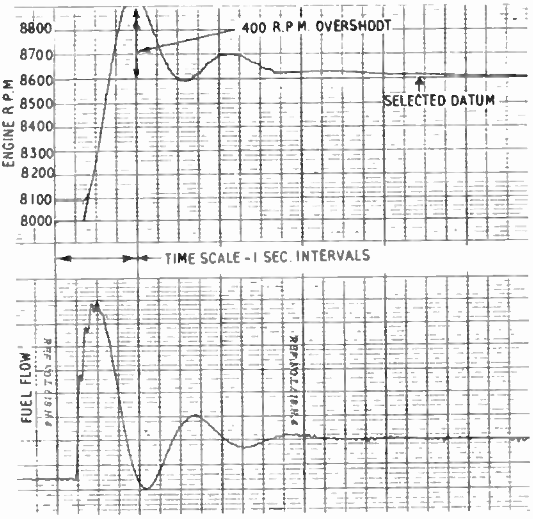

Fig. 11. Response of engine with addition of integrator—removal of steady state error.

also suffer and the system would become too sluggish. Alternative means must therefore be found to limit the overshoots.

The method to be described is an addition to the governor flyweight system. Use is made of hydraulic pressure for transmitting signals and bellows for changing the pressure into an applied force. The rate of change of engine speed, or derivative signal, is derived by measuring the force needed to accelerate a floating inertia weight at the same rate of acceleration as the engine. Fig. 12 illustrates how this force is measured.

The inertia weight is carried inside a rotating shell running on a direct drive from the engine, normally on an extension from the flyweight governor. Oil is supplied through the drive shaft and a fixed restrictor, to a pressure diaphragm and a variable restrictor. As the engine accelerates the inertia weight lags slightly so closing the variable restrictor.

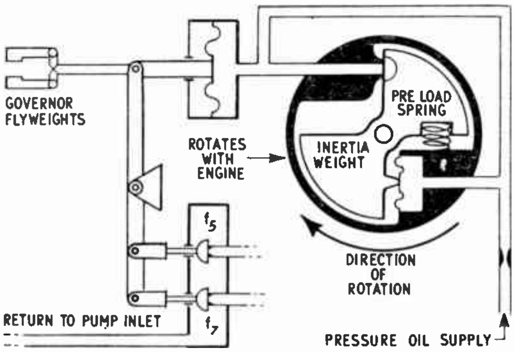

Fig. 12. Method of reducing overshoot of engine speed.

This builds up pressure in the diaphragm to apply an accelerating force to the inertia weight. When in equilibrium it is seen that the change of oil pressure in the diaphragm is always proportional to the rate of change of engine speed. This pressure is then applied to a second diaphragm on the governor arm to bias the force applied by the governor flyweights.

The signal applied to the governor arm is then proportional to the rate of change of engine speed, but because flow is required to inflate the diaphragm it is subject to a single inflation time constant.

The total effect on f_5 is then given by:

$$\Delta f_5 = \left[Z_1 + \frac{Z_3 p}{1 + \tau_3 p} \right] N_e + \frac{Z_2}{p} \, . \, N_e$$

where the second term in brackets represents the effect of the inertia weight.

On the computer set up in Fig. 8 this effect is introduced by adjustment of the potentiometer "*c*." Fig. 13 shows the results when the optimum setting of the potentiometer is chosen.

It is seen now that the overshoot has been restored to 240 rev/min with the proportional control of Fig. 9. This would still be too high an overshoot when accelerating to maximum revolutions although would probably be accepted for lower ranges. A non-linear means of reducing this overshoot at maximum revolutions is shown later.

Figure 14 shows the effect of the derivative term only on the proportional governor when it is seen that the overshoot is reduced from 240 to 160 rev/min.

Increasing the derivative term produces a de-stabilizing effect as shown in Fig. 15.

3.3. *Results of Linear Analysis*

Taking a survey of the results so far we can see how the response of the engine to a step change in throttle position (i.e. selected engine speed) has been improved by the addition of the modifying elements in the device closing the loop.

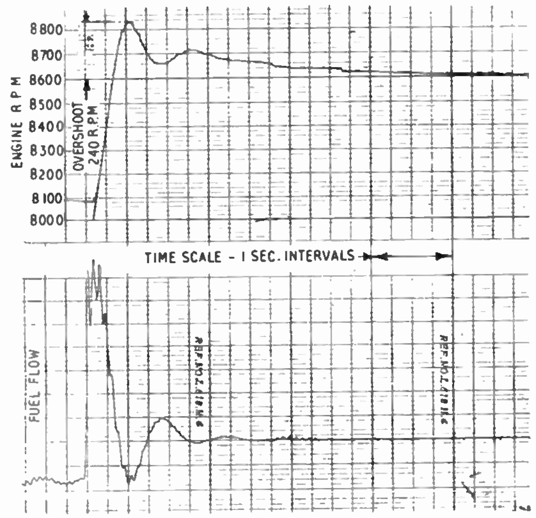

Fig. 13. Response of engine with addition of integrator and derivative term—zero steady state error and reduction of overshoot.

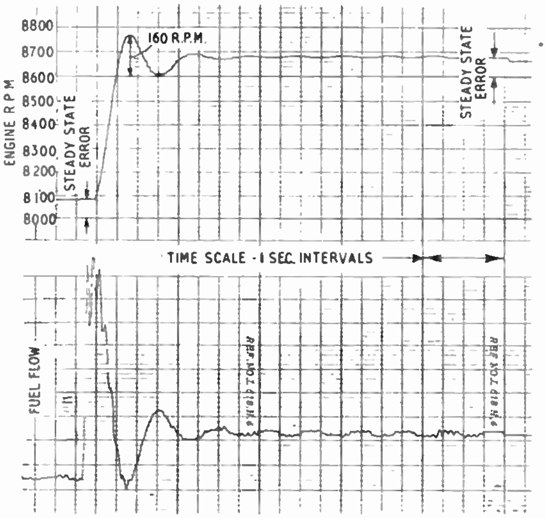

Fig. 14. Response of engine with proportional and derivative terms—reduction of overshoot to 160 rev/min.

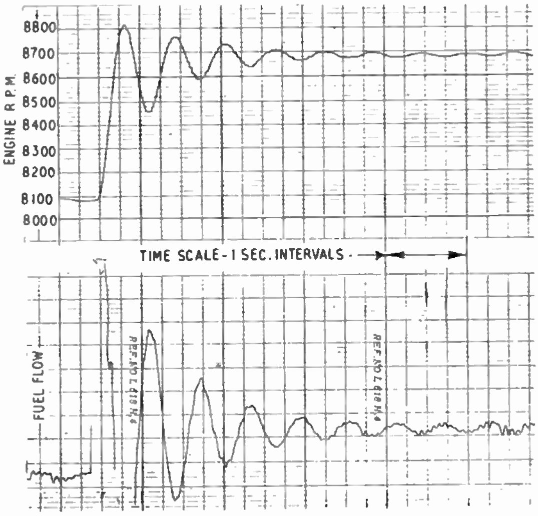

Fig. 15. Effect of increasing derivative term

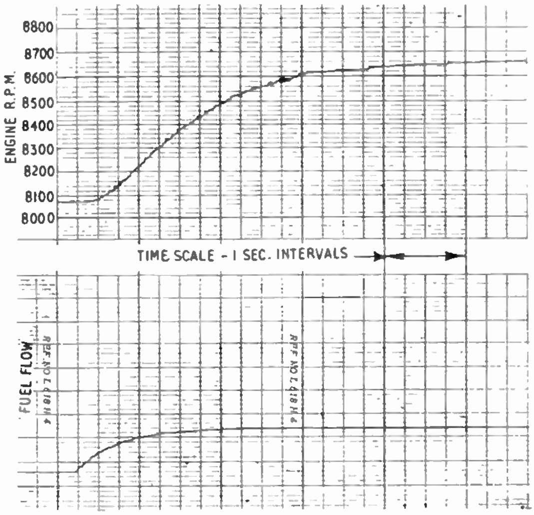

Fig. 16. Engine response with schedule system only.

When the optimum values have been chosen from this linear analysis the values of the constants can be specified and the detail design of the system components can commence.

For comparison the response of the engine with a scheduling system only is shown in Fig. 16 for a speed change of 600 rev/min when it can be seen at once how the response to throttle movement has been improved by the governor (see Fig. 13).

We have of course only considered one particular engine operating condition (namely, sea-level static) in our work given here. As stated before, the engine is to operate under many combinations of altitude and forward speed. Governing at different engine settings must be considered, and variation in the engine transfer function allowed for when the engine is used to supply power for aircraft services or compressed air for cabin pressurization, etc.

The study must cover all the possible variations before the constants for the various control components can be finally specified.

4. Introduction of Non-Linearities

When the work has progressed so far and the basic operating constants have been specified so that the mechanical design of the components can proceed, it is necessary to make a much deeper exploration of the system. In particular when the components have been given detailed design consideration, the possible sources of additional disturbances must be considered. The flow control and pump for example must be examined to assess where:

(*a*) friction forces may affect their operation;

(*b*) limitation of travel of valves and pistons may put restriction on the control;

(*c*) the types of valves proposed do not have linear characteristics;

(*d*) their position is to be affected by fuel pressures under the valve seats.

Where it is thought that any of the effects may constitute an important modification to the basic transfer function it is necessary to modify the constants given for the design of the system or recommend changes in the type of design to reduce their effects. In some cases, of course, the effect may be beneficial in which case recommendations can be made so that the effect can be retained as a design feature.

Finally consideration should be given to the possible introduction of deliberate non-linear effects. These may be used in certain cases to make further improvements in the system response.

4.1. *Examination of Practical Design Components*

Typical pump and flow control diagrams which illustrate practical designs based on the principles we have been considering are shown in Fig. 17, where it can be seen that many additional features have to be added to make the system a reality.

The need for the original simplified diagrams where basic considerations only are used can now be seen.

In considering the cases of the pump and flow controls as shown in Fig. 17 the following are the major non-linearities which should be considered and applied to the computer:

(*a*) Friction of seal on pump servo piston.

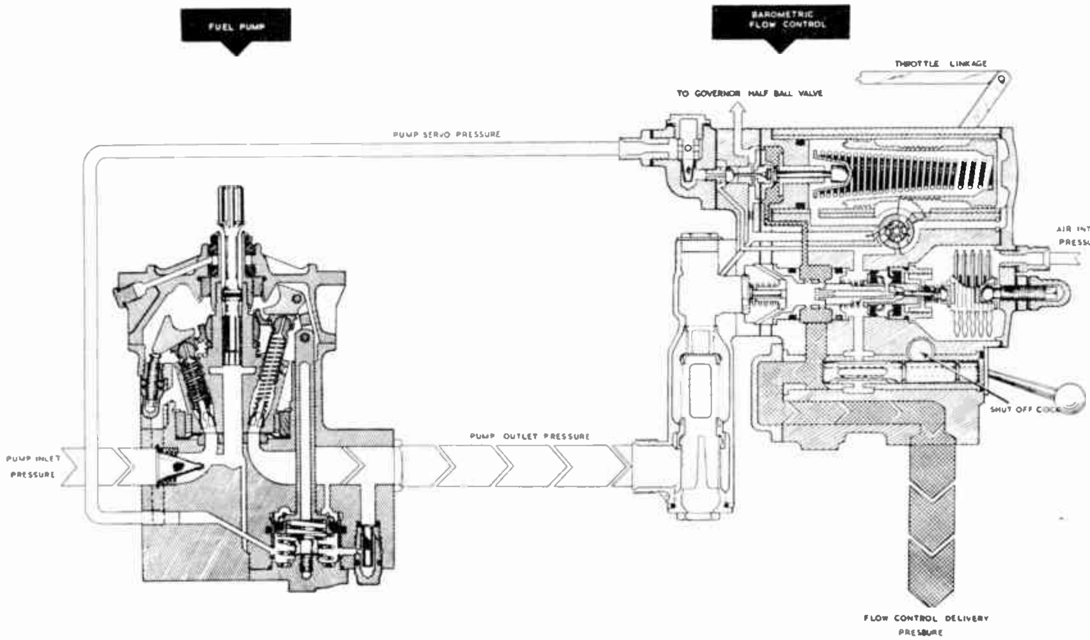

Fig. 17. Schematic diagram of components of hypothetical fuel system.

(*b*) Limitation of travel of pump servo piston. This provides a maximum fuel flow stop which may help to limit overshoots on acceleration to maximum revolutions.

(*c*) Limitation of travel on valve at the end of the pump servo pressure line. (This is shown as valve f_2 in Fig. 4.) The type of valve chosen is called a "half-ball valve" and the change of flow number is approximately proportional to the valve lift over a limited range.

(*d*) Friction in push rods between the half-ball valve, the diaphragm and the throttle spring.

A similar survey could be made of the other components in the system such as the governor arm and associated items previously discussed.

For the purpose of illustration we shall consider the effect of (*b*) above. Limitation of maximum fuel flow is used on some existing simple governor systems in order to achieve satisfactory handling without the use of derivative devices.

The way in which fuel flow limitation can affect overshoot of engine speed is shown by the computer results given in Fig. 18. This non-linearity has been applied to the computer set-up shown in Fig. 8. The results given are for proportional control only It can be seen that the maximum overshoot is reduced from 240 rev/min to 120 rev/min. A further improvement would be shown with the derivative and integral terms added bringing the maximum overshoot to acceptable limits.

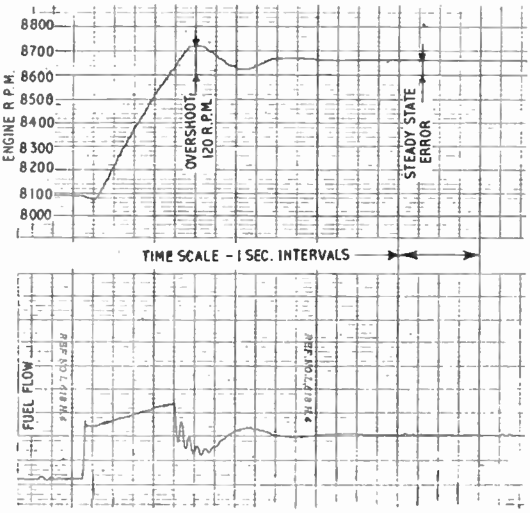

Fig. 18. Response of system with limitation on pump displacement.

Other non-linearities can be treated in a similar way on the computer.

5. The Present Position and Future Trends

The examples given in the preceding sections show in a general way the development of a suitable fuel governor system for an aero engine. The procedure followed illustrates how a system based on an initially conceived idea of a pump and flow control may be developed to give the required handling and stability characteristics. The full work would, of course, include considerations of altitude and high forward speed operation where the engine "gain" may cover the range from 2 to 10 and its main time-constant vary from 0·8 to 11 sec.

The system as determined for the sea-level case may require either some compromise in results to satisfy also altitude conditions or additional components may be required, so extending the procedure described.

The control engineer must of course bear in mind the many other requirements of the system in addition to the governing requirements and these must also be developed alongside the governing system.

The development of an aero engine from its initial project stage to bench and flight testing is a process occupying several years of work, and as yet a control system based on this type of investigation has not yet reached a testing state on a new engine. When such a stage is reached, considerable bench and flight testing time will be saved.

On systems which have been analysed by computer techniques equivalent test-bed running has shown results to be quite consistent, bearing in mind that the method still requires further development as mentioned below.

The importance of following up the analysis work with response testing as the manufactured components become available cannot be over emphasized. At its best, the mathematical analysis of the behaviour of each component must simplify the component. Any important deviations from the theoretical design therefore should be found as soon as possible so that

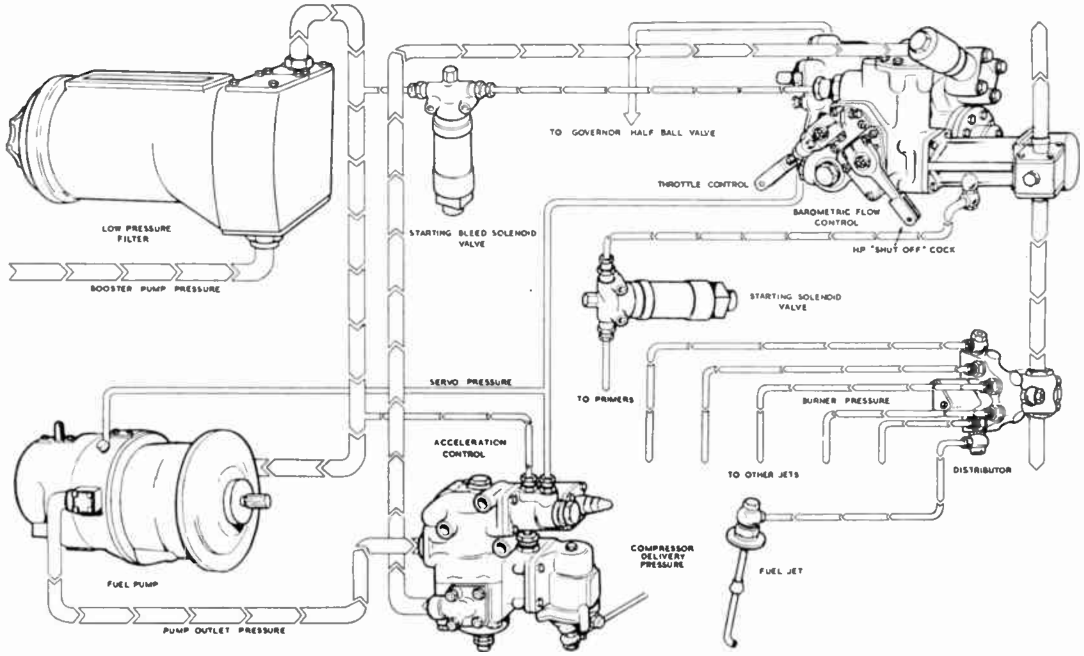

Fig. 19. Complete hypothetical fuel system

their effects may be studied. Where non-linearities are involved, the normal response testing techniques fall down since the output of the component is then sensitive to input amplitude as well as input frequency. It is therefore necessary to carry out response testing with varying amplitude as well as frequency.

In conclusion it will be an advantage to discuss briefly the way in which further development of computer techniques will enable more reliable predictions to be made. Accuracy is limited at the moment by incomplete knowledge of the engine behaviour when operating under transient conditions away from its normal steady state working line. The engine transfer function quoted earlier is true only for small disturbances and the values of the constants as well as the assumption of strict linearity must be in doubt for larger disturbances.

With the development of engine simulation over greater operating ranges will come the possibility of incorporating acceleration controls and the determination of the most desirable form of such controls. This is a subject which at the moment occupies a considerable proportion of the available flight testing time. Any assistance that can be given to reduce this testing therefore would be an advantage.

Figure 19 shows a complete fuel system (not including the governor) where other essential items have been included to show that the pump and flow control loop is but one consideration in the system. The other items are essential components which cater for the other running and starting problems on the engine, which require very full consideration but do not come under our present problem of governing.

6. Conclusions and Acknowledgments

Whilst present techniques for analogue simulation of aero engine control system problems provide very real assistance in system design, refinements are necessary, particularly in assisting the understanding of engine transient conditions.

As further non-linear effects are appreciated simulation techniques must be developed by co-operation between the computer designers and the control system engineers. The preparation of this paper has been an example of this co-operation and the authors are indebted to the managements of Elliott Bros. and Armstrong Siddeley Motors for permission to describe this work.

APPLICANTS FOR ELECTION AND TRANSFER

As a result of its October meeting the Membership Committee recommended the following elections and transfers to the Council.

In accordance with a resolution of Council and in the absence of any objections, the election or 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.

Transfer from Associate Member to Member

BURT, Sidney John George. *Hong Kong.*

PERKINS, Wilfred John. *Stanmore.*
PINK, Richard Alfred Peter. *Surbiton.*

Direct Election to Associate Member

CHAGHTAI, Flt. Lt. Mirza Sikandar Beg, M.Sc., Ph.D., Pakistan Air Force. *Gujranwala.*

FORSTER, James Frederick Stanley. *Bexleyheath.*
FRY, Wilfrid John. *Burpham.*

HANN, Arthur, B.Sc. *Luton.*

LAW, Flt. Lt. Edward Arthur, B.Sc., R.A.F. *Weston-super-Mare.*
LEWIS, Commander Richard, R.N. *Havant.*

MARSDEN, Bernard. *London, N.W.8.*
MILLAR, Flt. Lt. Guy Hollington R.A.F. *Glasgow.*

TILSLEY, David Newman, B.Sc. *London, S.E.24.*

Transfer from Graduate to Associate Member

BARTLETT, Haroun Bey. *Leamington Spa.*

DOUGHTY, Donald John. *Greenford.*

MACKENZIE, George White. *Evesham.*

RICHARDSON, Leslie. *Banstead.*

STUBBS, John. *Liverpool.*

TAPP, Lieut. Edward William, R.A.N. *Worthy Down.*

VENKATESWARAN, Flt. Lt. Gopalakrishnayyar, M.A., B.E., I.A.F. *Cranfield.*

Transfer from Student to Associate Member

HARRIS, Aubrey. *Chelmsford.*

Direct Election to Associate

AHMAD, Muzaffar-ud Din, B.A. *Karachi.*

BAKER, Richard James. *Basingstoke.*

CALCROFT, Norman. *London, S.E.3.*

HARVEY, John Rattray. *Stanmore.*

SWAN, William Ralph. *Fareham.*

TINDALL, Bryan Frank, B.Sc. *Farnborough, Hants.*

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AUTOMATIC ULTRASONIC INSPECTION[*]

by

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A paper presented at the Convention on "Electronics in Automation" in Cambridge on 28th June 1957. In the Chair: Mr. E. E. Webster (Member).

SUMMARY

Manual ultrasonic flaw detection has been employed as an industrial inspection method for several years. Using this technique very high standards of inspection were maintained. It is however not suitable for modern high speed production conditions. The factors limiting the application of manual inspection under these conditions are considered and a description given of the fully automatic equipment recently developed to overcome these limitations.

1. Introduction

The first commercially-available pulse echo equipment using high-frequency sound waves for the detection of internal defects in metals was produced in 1942. These equipments were immediately and successfully used to detect hairline cracks in armour plate and internal cracks in extruded light alloy aircraft main spars. Since that time ultrasonic inspection techniques have been applied to a diverse range of materials and production processes. The instruments and techniques have been developed continuously resulting finally in a range of equipment which is capable of inspecting automatically and rapidly a wide range of materials to a consistent but adjustable sensitivity.

Ultrasonic inspection, as its name implies, uses a beam of high-frequency sound waves to detect the presence of discontinuities in the material under test. An inspection probe coupled to the surface of the material by a liquid generates the ultrasonic sound as a sequence of pulses which are transmitted into the material. When these pulses reach the opposite face they are reflected and return to the probe, the time taken being dependent on the velocity of sound waves in the material and its thickness. This sequence of events can be displayed as a trace on a cathode-ray tube (Fig. 1 (*a*)), vertical deflection of the trace indicating the amplitude of the echo and the horizontal deflection of the trace being proportional to elapsed time giving the conventional A-scope presentation. If any discontinuity is present some energy will be reflected by it and returned to the top surface before that from the boundary, giving rise to the trace shown in Fig. 1 (*b*). An operator manipulating the inspection probe and interpreting the successive indications obtained upon the cathode-ray tube can in many cases determine the position, approximate size and orientation of a defect in the material.

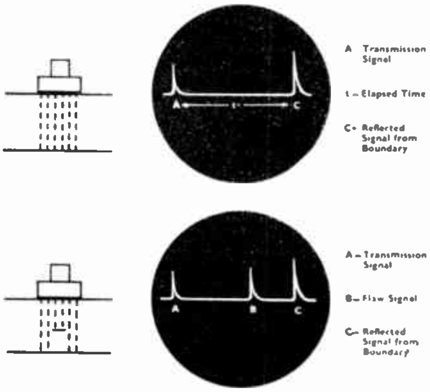

Fig. 1. Typical cathode-ray tube traces for manual ultrasonic inspection.

A block diagram of a typical commercial ultrasonic flaw detector is given in Fig. 2. The pulse transmission rate control unit determines the number of pulses of ultrasonic waves

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generated per second; on the initial models, this rate was fixed and locked directly to the 50 c/s a.c. mains. The pulse transmission rate unit triggers first the time-base generator which deflects the cathode-ray tube spot across the screen of the tube. Secondly, it triggers the ultrasonic pulse generator which electrically excites the piezoelectric crystal in the inspection probe so that it emits a heavily damped pulse of ultrasonic sound. If the rate of movement of the spot across the tube is adjusted so that its time of travel is slightly greater than the time taken for the waves to travel through the material and return to the top surface after reflection at the bottom, the traces shown diagrammatically in Fig. 1 is obtained. The range of a defect in the material can be estimated, therefore, directly from its position as indicated on the cathode-ray tube trace.

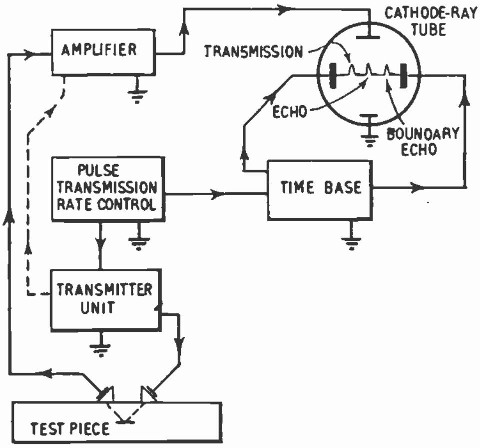


Fig. 2. Block diagram of ultrasonic flaw detector.

At its inception, ultrasonic inspection was applied to two commodities but during the War and afterwards it was applied to a very wide range which included: steel bars, ingots, blooms, forged rotors, cast and forged rolls, forgings, rolled bar, rolled sections, plate, light alloy extrusions, forgings, castings, plate and bar, concrete, ceramics, graphite blocks, living and dead timber, plastics, welds, etc.

It is obvious, therefore, that the manual system of ultrasonic inspection became a fully recognized and applied industrial inspection tool. In the last few years it has been used increasingly as a means of assessing approximately, but in certain cases rapidly, the change in quality of a product brought about by alteration in production conditions. While it is not possible as yet to obtain an absolute measure of quality by these techniques, a skilled operator can obtain a very good assessment of the location and degree of porosity present in, for example, a cast light-alloy billet without need for expensive sectioning and etching of the material. Under controlled conditions an operator can predict by ultrasonic measurement the ultimate tensile strength of certain metals or the crushing strength of concrete.

During the last few years there has arisen an increasing demand from designers that the material used in their structures should be free from defects and be of uniform quality. This pressure for the production of material of high quality is particularly noticeable in the aircraft industry where it is essential for the designer to eliminate excess weight so as to give aircraft the highest performance in terms of speed, or load carrying ability, while at the same time maintaining an adequate factor of safety. To satisfy these requirements it is essential, therefore, that the material of the aircraft be stressed to its safe limit and that there be no defects present which will lower this. In addition in other fields where the strength requirements are not so stringent it is becoming apparent that there is also a growing demand for material free from defects and uniform in quality so that the running costs of a manufacturing process can be reduced. A particular example of this is in the deep drawing of components from sheet material where, if the sheet is laminated, some of the laminated material may chip out of the surface during the drawing process and adhere to the punch tool or die; when the next sheet is drawn this excess material may overstress the punch and die unit and fracture the expensive tool assembly.

Before considering the factors which limit the application of manual ultrasonic inspection techniques under modern industrial high-speed production conditions, it must be emphasized that the days of this method of flaw detection are not limited: as its operators become more skilful and the instruments more refined its usefulness and applications will increase even further. All subsequent criticisms of the manual technique are justified only by reference to the inspection requirements of modern high speed production.

2. Present-day Inspection Requirements

An inspection technique should reveal the position of any significant internal discontinuity in the material under test. It should be automatic and capable of being integrated into the production schedule of a modern high-speed process. It should maintain a consistent standard of inspection and provide immediate warning if the system should fail. It should assist the development of production processes by providing continuous information on the quality of the material, thus allowing the accurate assessment of the effect of production changes on the quality of the product.

Manual flaw detection cannot meet these requirements even when it is most carefully and consistently applied, as it has the following limitations.

It is a system dependent on the operator maintaining a constant watch on the cathode-ray tube and at the same time manipulating inspection probes on the surface of the material. It is possible, therefore, for small but significant defects to pass undetected due to the attention of the operator being momentarily distracted from the screen, to the incorrect manipulation of the probes or to an area of the surface being unexplored.

Manual operation of the inspection probes makes it difficult to maintain consistent coupling between the probes and the material under test and as a result the standard of inspection is liable to vary from point to point on the surface of the material. In addition the operator becomes fatigued after extended periods of testing and then his standard of inspection falls rapidly. Manual operation is slow and therefore unsuitable for handling a large volume of production unless many inspection units are employed in parallel. This system requires very strict control of testing conditions to ensure a consistent standard of inspection between adjacent units. Under these conditions manual inspection is generally used to sample rather than provide continuous control of quality.

3. An Automatic System of Ultrasonic Inspection

Because of the limitations of the manual system of ultrasonic inspection, the development of the Autosonic range of non-destructive testing equipment was initiated. These equipments overcome all of the disadvantages of manual inspection procedures detailed in the previous paragraph, as they are fully automatic, thus eliminating the effect of operator fatigue on the inspection standards. The electronic circuits ensure that a preset standard of inspection is maintained and that immediate warning is given if the acoustic inspection system fails. It is a high-speed inspection technique and as a result can be arranged as an integrated part of a modern production process. Recording systems are available which will provide a permanent record of the quality of the material tested. The equipment is easy to adjust and is easy to service in the event of failure.

The equipment combines the techniques of acoustics, electronics and mechanical manipulation. After a simple initial setting-up procedure, the electronic control circuits replace the operator, performing his functions with rapidity, certainty and accuracy. The setting-up procedure is made easy by the method of presentation on the cathode-ray tube screen, e.g. in a single channel equipment there are two sections of the trace which are brighter than the rest and define the position of the electronic gates which are essential to the operation of the succeeding automatic circuits. The first bright portion of the trace or gate selects defect indications from all or part of the cross-section of the material, rejecting those indications which are smaller than a preset value, operating a flaw alarm or recorder system for all defect indications greater than the preset value. The second bright portion of the trace or gate selects a given signal and measures its amplitude, immediately altering the sensitivity of the equipment to compensate for any change in the amplitude of this monitor signal. If the amplitude of the monitor signal should decrease beyond the range of the automatic sensitivity control circuit to compensate for it, then the system failure alarm warning will operate and stop the inspection process.

One function of the mechanical section of the Autosonic equipment is to move the inspection probe rapidly over the surface of the specimen according to a predetermined pattern. The choice of inspection pattern will naturally vary considerably depending on the nature, number and distribution of the probable defects present, the exact mechanical arrangement employed will depend on the application.

4. The Acoustics Section of the Equipment

The acoustics section or inspection probes of the Autosonic equipment generates, transmits and detects the pulses of ultrasonic sound waves used to reveal the presence of discontinuities in the material under test. These pulses must be as short as possible to give the required resolution between adjacent small defects in the material. This is a particularly stringent requirement where material is going to be heavily machined before it is finished; here the producer wishes to determine the position of the defects accurately because if they are to be machined out and are small they are of no consequence and the material can be used.

The ultrasonic pulses are produced by the electrical excitation of natural piezoelectric materials such as quartz lithium sulphate, or in recent years a sintered ceramic electrostrictive material, barium titanate. These crystals are charged to a high potential and are then discharged periodically by a thyratron valve. The discharge of the voltage causes the crystals to vibrate and emit an ultrasonic pulse 5 to 20 wavelengths long. For a crystal generating longitudinal waves, the ultrasonic frequency is determined by the thickness of the crystal; at the present day frequencies in the range 60 kc/s–25 Mc/s are used to inspect material.

A short ultrasonic pulse can only be produced by a broad band or low Q transducer. The Q of the transducer is lowered by bonding it to a backing block made from material of approximately the same acoustic impedance but having high internal damping. (A section through such a loaded transducer is shown in Fig. 3). The loading material is commonly made from a mixture of a moulding resin and a finely powdered metal such as tungsten or carbonyl iron. The length of the backing block is sufficient to attenuate adequately any ultrasonic pulse before it is reflected from the end of the block and back to the crystal. This backing block considerably reduces the effective length of the pulse, at the expense, of course, of the sensitivity of the probe. The advantages of the increased resolution, however, outweigh the disadvantage of decreased sensitivity, particularly where flaw analysis is important.

In all automatic ultrasonic inspection it is desirable that the coupling between the inspection probe should be consistent and allow the probe to be moved at high speed over the surface of the material under test. Two coupling systems are used extensively at the present time, firstly, the so-called "gap scanning technique." and secondly, the "immersion technique."

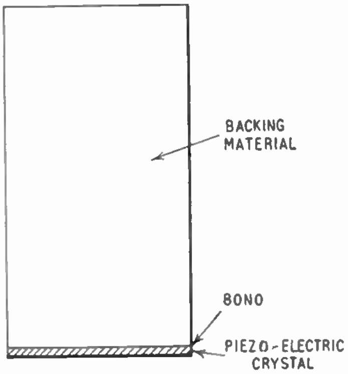


Fig. 3. Section of loaded transducer.

In the first system, the inspection probe is supported a short distance off the surface of the material, the gap between the probes and the surface of the material being filled with a liquid meniscus (see Fig. 4). Practical tests have shown that this meniscus can be maintained satisfactorily by a small water feed even at very high scanning speeds. This type of scanning system can only be used satisfactorily with separate or combined transmitting and receiving probes. If a single probe is used reverberation occurs in the thin liquid film, causing the ultrasonic pulses to be considerably extended, thus reducing the resolution of the inspection system and particularly affecting the minimum range at which a defect can be detected.

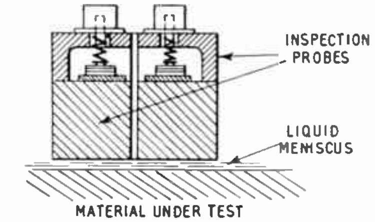


Fig. 4. Schematic sketch showing gap scanning of plate material.

In the second system, the material to be tested is immersed in a tank of water and the probe is acoustically coupled to the material by a layer of water which can be several feet thick if necessary. The minimum thickness of the water layer must be such that the time for the pulse to traverse this layer is at least that taken to traverse the material, otherwise multiple reflections from the first water/material interface cause difficulty in interpreting the indications on the cathode-ray tube. This type of coupling can be used with both separate transmitting and receiving probes or combined probes.

An attempt to combine the advantages of the two coupling systems just described is the so-called "jet coupling." In this system the probe is supported several inches off the surface of the material, acoustic contact being maintained by a jet of water. This system can be used with either a single or double probe inspection system, but considerable difficulty has been found in practice in maintaining a column of water in which the flow is free from turbulence and air bubbles. As a result of these difficulties this system has not been employed very extensively.

Ultrasonic waves suffer reflection, refraction and scattering like light waves. However, for certain angles of incidence on an interface, as well as refraction and reflection of the beam occurring, some of the energy is transformed and propagated in an alternative mode in the second medium (solids can support both longitudinal and shear stresses). This transformation effect is used to produce shear or surface waves from a crystal generating longitudinal waves when required for the inspection of materials. Table 1 lists the wavelengths and ultrasonic velocities in a range of common materials. Fig. 5 shows graphs of incident to refracted angle for various materials.

The transfer of energy across an interface is governed by the acoustic impedances of the two materials. The specific acoustic impedance of a material is defined as the product of its density and the velocity of the sound. For normal incidence of the sound beam, the energy reflected is given by

$$\left(\frac{\rho_1 C_1 - \rho_2 C_2}{\rho_1 C_1 + \rho_2 C_2}\right)^2$$

For materials such as water and aluminium, the energy transmitted into the aluminium is only 19 per cent. of the incident energy.

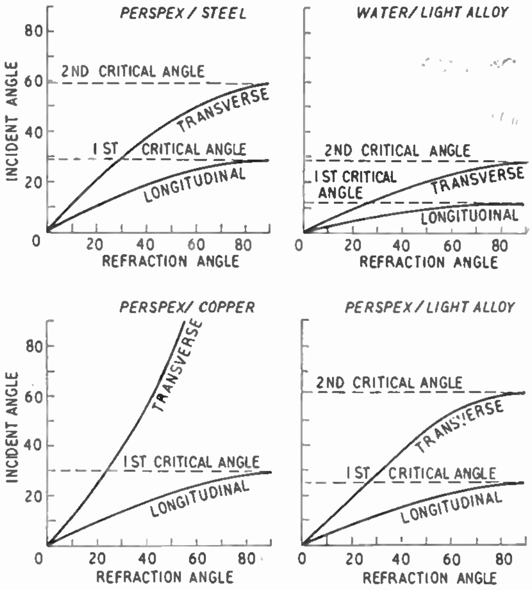


Fig. 5. Relation between incident/refraction angles for some common materials.

This loss can be reduced by using mechanical matching impedances between the two media. These matching impedances are made from layers of material with acoustic impedances intermediate between the two media, e.g.

perspex assists in matching a barium titanate crystal to water under immersion testing conditions. The relations governing the choice of matching impedances are similar to those involved in matching electromagnetic transmission lines of different impedance.

Many physical arrangements of inspection probes are possible, but they can be grouped under the three following headings:—

(1) Single probe (common transmitter/receiver).
(2) Double probe or separate transmitter/receiver.
(3) Combined probe (separate transmitter/receiver but combined in a compact single mounting).

Throughout the development of the technique of ultrasonic inspection there have been protagonists of the three types of probes. It is felt that in fact each type of probe has its particular sphere of operations and their advantages and disadvantages may be briefly summarized.

First the single probe is very convenient to handle and operate and can be made extremely small and thus can be used in confined spaces. It has the disadvantage that as the transmission pulse is applied to the crystal it is also applied to the input of the highly sensitive amplifier This means that this amplifier is blocked for some time, during which it cannot receive any signals and thus give warning of the presence of a defect near the top surface of the material. This results in a dead zone immediately under the top surface. A further serious disadvantage is that the inspection is made from a single viewpoint and is thus limited in the information that can be obtained.

The double probe using the separate transmitter and receiver has the advantage that the transmission pulse is only applied to the transmitting crystal and there is therefore no blocking of the receiving amplifier. By suitable design of these probes it is possible where required, therefore, to reduce the dead zone to a very small value indeed. In addition, as the two probes are separate it is possible to inspect the interior of the material from widely differing test positions and thus obtain the maximum possible information on the orientation and nature of defects present. It is possible to "focus" the probes on a particular zone in the material, maintaining high sensitivity at this zone and lower sensitivity in the remaining zones. Naturally two probes are always larger than one, and in many instances the two probe system cannot be used owing to the small testing space available.

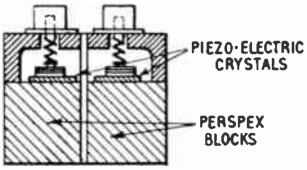


Fig. 6. Section through combined probe.

The combined probe with the separate transmitter and receiver mounted in a common holder has been used for some considerable time in an attempt to combine the advantages of the single and double probes and recent advances in the design of combined probes has enabled this to be achieved. An inspection

Table 1

Velocity of ultrasonic sound waves in some materials and the wavelengths at 1 Mc/s

	Velocity $\times 10^{-5}$ cm sec^{-1}			Wavelength in mm at 1 Mc/s		
Material	Longitudinal	Transverse	Surface	Longitudinal	Transverse	Surface
Aluminium (1)	6·32	3·10	2·92	6·3	3·1	2·9
Steel (1)	5·94	3·22	2·98	5·94	3·22	3·0
Glass (1)	5·80	3·35	3·08	5·8	3·35	3·1
Perspex (3)	2·81	0·92	—	2·81	0·92	—
Water (6)	1·49	—	—	1·49	—	—
Mercury	1·45	—	—	1·45	—	—

system using this universal type of probe (Fig. 6) has an extremely small dead zone and excellent sensitivity. An example of the response of this probe to small targets in light alloy is shown in Fig. 7. It must be emphasized in these tests that over the range from 0·1 in. to 8 in. the indication from the amplifier is not overloaded and it is thus possible to achieve size resolution at any point in this range without resetting the gain of the amplifier.

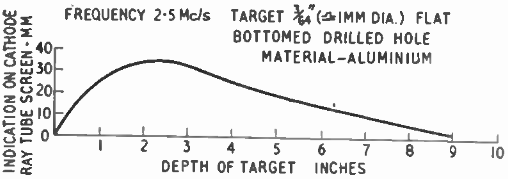


Fig. 7. Typical characteristics of universal vlo probe—20 mm-10 mm barium titanate transducers.

An important aspect of Autosonic inspection is the maintenance of uniform standards of inspection as will be discussed in the electronic section. Particular attention has been paid to this in the Autosonic equipment, but there is still need for some means of calibrating the sensitivity of the equipment at the start of the test. At the present day this is achieved by means of calibration blocks. A number of different designs for these units have been proposed for different applications, e.g. at the present time blocks of material with a flat bottomed drilled hole are used generally for this purpose in the light alloy industry. A diagrammatic section showing the arrangement of the hole in the block is shown in Fig. 8. The preparation of these blocks involves considerable skill, as quite small radii on the edges of the hole will materially affect the amplitude of the indication obtained from it. A word of warning should be issued concerning the use of these test blocks. They have in many instances induced a false sense of security in that users have tended to claim that the size of a defect producing the same indication on the cathode-ray tube screen as a hole in a standard test block means that the defect is of the same area. Unfortunately this is an unjustified assumption. While in many cases there is good correlation between the two indications, changes in the character of a defect can destroy this correlation completely. Therefore all that can be reliably claimed for these test blocks is that they are a means of ensuring that the equipment is set up and continues to function at a constant sensitivity from day to day. From experience and assuming that there are no changes in the production conditions it then becomes possible also to obtain a fairly accurate idea of the size of discontinuities present with reference to these blocks.

A very interesting alternative design of test block is the so-called suspended target block. In this block a series of laminar targets are supported on fine tubes. A cylinder is filled with liquid and by varying the depth of the liquid the distance between the probe and the target is conveniently altered. Such a block has two advantages compared to the solid block as, firstly, continuous variation of the range of the target is possible by varying the depth of liquid in the cylinder, thus eliminating the need for multiple blocks, and secondly, the coupling between the probe and this test block is much more consistent than the solid block.

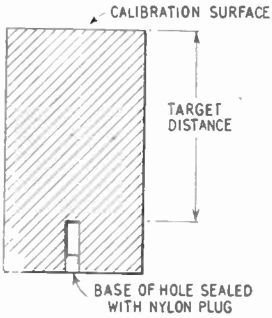


Fig. 8. Section through ultrasonic test block showing flat bottomed drilled hole.

5. Electronics Section

A block diagram illustrating the operation of the electronic section of the Autosonic equipment is shown in Fig. 9.

A pulse from a repetition rate control circuit in the display unit initiates the inspection sequence by first triggering the transmitter unit and thus generating an ultrasonic pulse and secondly the time-base waveform generator.

A second pulse derived from the transmitter unit initiates a series of timing waveforms which are used to control the flaw warning and monitor gated amplifiers. These waveforms are also applied to the modulation grid of the cathode-ray tube to "bright up" the trace and indicate clearly the position where the flaw warning and monitor gated amplifiers are working.

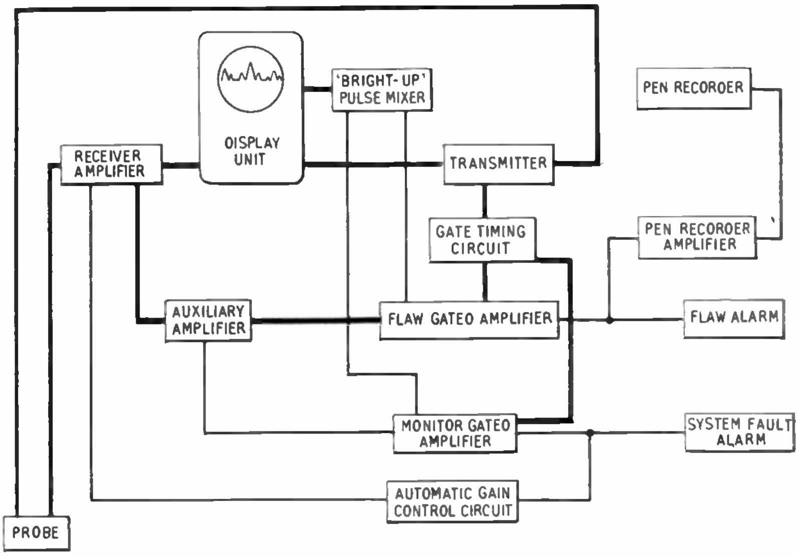


Fig. 9. Schematic diagram of Autosonic unit.

The ultrasonic pulses obtained from the material after amplification are applied to the vertical plates of the cathode-ray oscilloscope, while the time-base waveform is applied to the horizontal plates to give the familiar A-scope presentation. The output voltages from the main amplifier are also applied to the flaw-gated amplifier together with the appropriate timing waveform, and if the signal occurs in the inspection zone in the material and is of sufficient amplitude, the flaw-gated amplifier will operate the flaw warning, marking or recording systems. Using the combined probe and searching for small targets material can be inspected from 0·1 in. below the top surface to within 0·1 in. of the bottom surface, the maximum thickness of material being 36 in., the minimum thickness of zone which can be inspected being 0·1 in. which can be located anywhere in the cross-section of the material.

The monitor-gated amplifier selects a given signal received from the material and measures its amplitude. If it should change from its initial value then the monitor amplifier alters the bias applied to the input stages of the main amplifier and corrects any change observed. This monitor correction system is very accurate and corrects the gain of the amplifier after every transmission sequence is completed, i.e. pulse by pulse. Thus the correction made by this amplifier is immediate and no error can be introduced at high scanning speeds of inspection due to rapidly alternating surfaces of poor and good transmissibility. The dynamic range of the monitor amplifier is satisfactory and an example of the correction is shown in Fig. 10.

This monitor circuit is arranged also so that, in the event of the monitor echo falling outside the correction limit of the automatic gain control system, a system failure alarm will operate. This can take the form of flashing lights or hooters or, if necessary, result in a complete shutdown of the inspection process.

The choice of the monitor signal used in the inspection system is one requiring care, as it must be a reliable measure of the sensitivity of inspection. When inspecting material of rectangular cross-section the lower boundary echo is an obvious choice and is generally used as such in the Autosonic equipment.

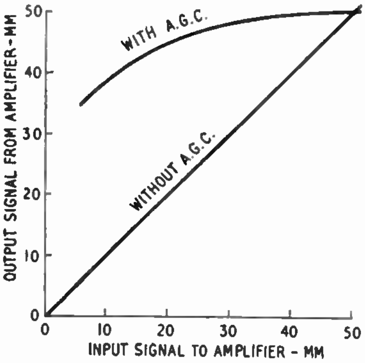


Fig. 10. Effect of a.g.c. on indications from amplifier as input signal is reduced

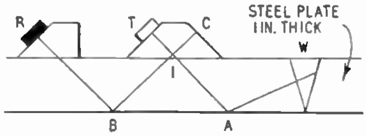


Fig. 11. Arrangement of probes for the inspection of a fusion butt weld.

Generally when inspecting a fusion weld in thick steel there is no echo equivalent to the lower boundary echo which can measure the sensitivity of inspection. In the inspection of butt welds, this difficulty is overcome by the probe arrangement shown diagrammatically in Fig. 11. The ultrasonic pulse from the transmitter T is reflected and repeated at the interface, the refracted ray is transmitted into the steel plate as a shear wave and after a reflection passes through the welded region W. If a defect is present some of the pulse will be reflected and this signal will reach the receiver R by the route, W A I B R. The reflected beam at the interface I, is reflected again internally at the face C of the transmitting probe and reaches the receiving probe R after reflection at B. The sequence of echoes received at R is given diagrammatically in Fig. 12. The monitor echo arrives considerably earlier than the flaw indications. No claim is made that this is a perfect system, but experience has shown that its use does result in a great improvement in uniformity of inspection as the results of Fig. 13 show.

Another difficulty arises when inspecting material which may contain gross defects such as lamination in steel plate. If such a defect is present it will reflect all the ultrasonic sound and there will be no boundary echo to monitor the sensitivity of inspection and as a result the system failure alarm will be brought into operation. In practice this state of affairs is avoided by arranging that the monitor gate covers the zone from just below the top surface to the low boundary surface. Under these conditions, when a gross defect is present, the lower boundary echo or monitor is replaced by the indication from the flaw. This arrangement does result in a change of sensitivity but this effect is insignificant when considering the nature and size of the defect detected and it has the advantage that the system failure alarm is not brought into operation until the system does break down.

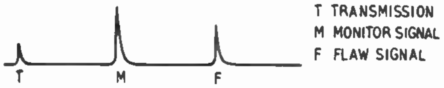
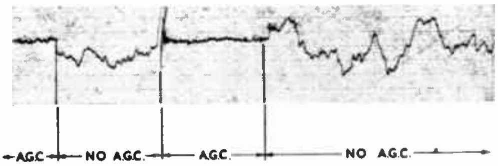
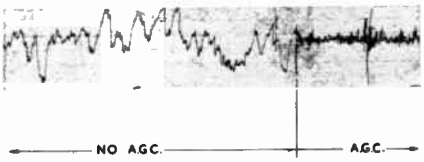


Fig. 12. Display on cathode-ray tube when inspection fusion butt weld in steel plate.



PROBE MOVEMENT ONE FOOT PER MINUTE.



PROBE MOVEMENT THREE FEET PER MINUTE.

Fig. 13. Improvement in reproducibility of indications obtained using the automatic sensitivity control system.

Three electronic presentations are available with the Autosonic equipments—A, B and C scans. The A-scan is the standard presentation (see Fig. 1) used primarily to adjust the sensitivity of the Autosonic equipment. The B-scan is an intensity-modulated display giving on a long-persistence cathode-ray tube a comprehensive picture of the cross-section of the material under the inspection probes. This system of presentation is extremely valuable when the operator has to detect visually the presence of defects in material which must be inspected at high speeds. However it is felt that this form of presentation has very limited application in rapid inspection systems as the automatic sensitivity control, flaw alarms and marking systems eliminate the need for close visual supervision of the cathode-ray tube indications. However for the analysis of flaws in some components the B-scan presentation can offer some advantages over A- or C-scan presentations.

The C-scan or p.p.i. presentation provides an indication of the area of the defects present in a plate, but no direct indication of their depth in the material.

In many instances it is essential to have a permanent record of the inspection carried out. The indications of the cathode-ray presentations just described can be photographed but generally a recording system which does not require any further processing to obtain a permanent record is preferred. Accordingly a number of systems are available which give a permanent record on Teledeltos paper of the flaw indications obtained. They are single or multi-pen recorders giving a record of defect indications together with linear position referred to a single inspection scan of the probe. It is thus possible to examine this record later and classify the size of defects present from the indication of the trace.

Very often the producer wishes to record the depth of the defects in the material. This can be achieved using multi-channel flaw alarm circuits, each adjusted to operate at different zones in the material and each coupled to a pen recorder.

For recording the presence of laminar type defects in plate the p.p.i. or C-scan recording system is much more convenient, and as such is generally employed. Examples of such a record obtained on a laminated steel plate are shown in Fig. 14.

Figure 15 shows the practical layout of the Mk. I electronic console unit. In operation only the cathode-ray tube screen is visible through a viewing tunnel and the recorder through a window. All controls are hidden to prevent unauthorized adjustment. On lifting the lid, controls are exposed which are used to set the flaw, monitor gate positions and system failure alarm, and to adjust the ultrasonic flaw detector section. A third range of controls which only require occasional adjustment become available after lowering a sliding door.

The individual electronic sections are arranged as follows. The display unit is mounted on trunnion bearings so it can be rotated to provide access to any part which may require servicing. The flaw alarm circuits, monitor amplifiers and recording amplifiers are mounted in individual chassis, which are in turn mounted on a larger chassis. The whole of this chassis can be swung out to permit easy access to each circuit. The single pen recorder is mounted on a slider and can be withdrawn from the cabinet after lowering the small sliding door in the front. The power supplies for the unit are fully stabilized and are mounted on the floor of the cabinet.

In this installation particular attention has been paid to the provision of test points and easy access to these points when servicing of the equipment is necessary. Experience to date shows that these test points are not required very frequently as each unit after installation has given trouble-free service.

6. Mechanical Section

The design of this part of the equipment must be very carefully considered if full advantage is to be taken of the performance of the acoustics and electronics sections of the Autosonic equipment. The mechanical section must move the probe assembly over the surface of the material (or vice versa) in a rapid and consistent manner. It must be easy to load and unload the material from the inspection

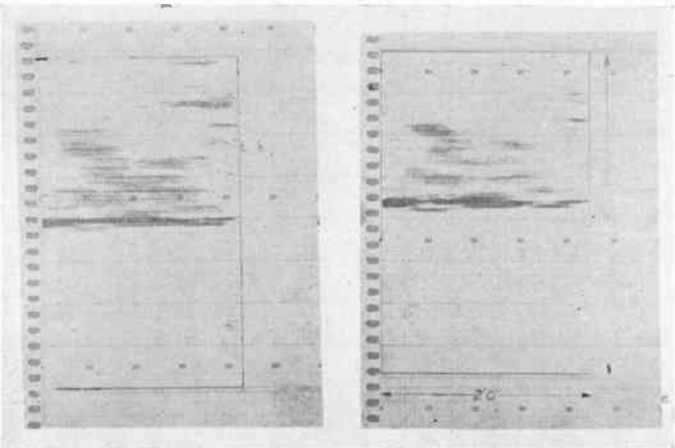
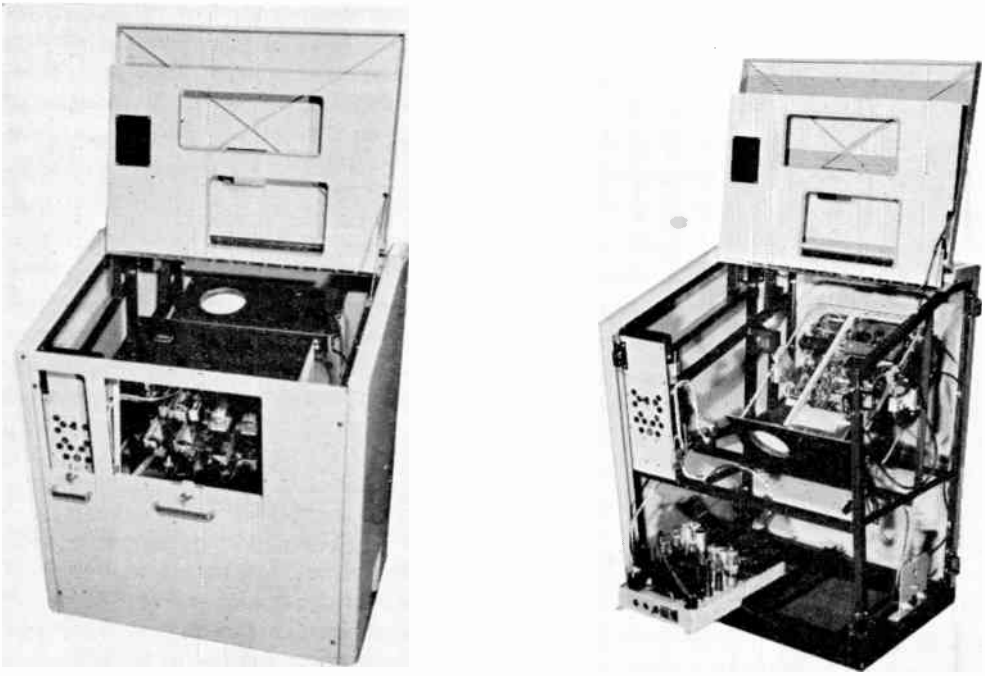


Fig. 14. Plan position recording of laminar type defects in a steel plate.



(a) (b)

Fig. 15. The electronic console unit (*a*) showing preset controls inset behind sliding door. (*b*) Arrangement of chassis in console.

area, as experience indicates that generally it takes longer to position the material for inspection than to inspect it unless considerable thought is given to the handling of the material to be tested.

Fig. 16. Automatic scanning equipment.

An example of one form of mechanical scanning equipment employing immersion techniques for testing light-alloy billets is shown in Fig. 16. It consists of a twin longitudinal carriageway carrying a transverse bridge; mounted on the transverse bridge is the transverse motor unit. This unit is used to mount the inspection probes.

The inspection of the billet is carried out using a common transmitter-receiver crystal mounted on the transverse motor unit. The transverse motor unit is locked in position on the transverse bridge and the aluminium billet is rotated as the transverse bridge carries the probe parallel to the axis of rotation of the billet. This system ensures that the full interior of the billet is surveyed. In many instances this complete inspection is not justified, the nature of the production process being such that only centrally-disposed cracks are produced. Under these conditions a simpler scanning procedure is justified and when only the central position of cylindrical specimens is to be tested then the probe arrangement shown diagrammatically in Fig. 17 has been used successfully.

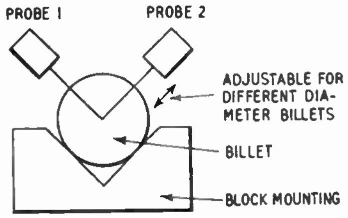


Fig. 17. Schematic diagram showing inspection system for the detection of central cracks in cylindrical materials.

Probes 1 and 2 are two common transmitter-receivers operating in parallel. This arrangement ensures that positive indications are obtained of centrally disposed cracks whatever their orientation without the need for rotating the billet. An example of a typical inspection arrangement for extruded or rolled bar is given in Fig. 18.

The inspection of the plate is carried out using a combined transmitter-receiver probe, mounted in the pantograph attached to the second tool post on the transverse motor unit. The transverse motor unit oscillates rapidly to and fro across the transverse bridge while this bridge moves over the plate. The results of such an examination are shown in Fig. 14 where the transverse motor unit was operating at 50 ft/min and the transverse bridge at 10 ft/min. On commercial installations the operating speeds can be of the order of 100 ft/min along both axes when required.

Figure 19 illustrates gap scanning of plate material and Fig. 20 shows an equipment designed to inspect plates on the roller table of the mill. The gap scanning probe is carried by a transverse motor unit mounted on the transverse bridge which moves on rails along the roller table. This installation is an example of the inspection forming an integrated part of the production process.

7. Conclusions

In conclusion, it is hoped this broad survey of the development of the Autosonic range of equipment has served to illustrate its practical

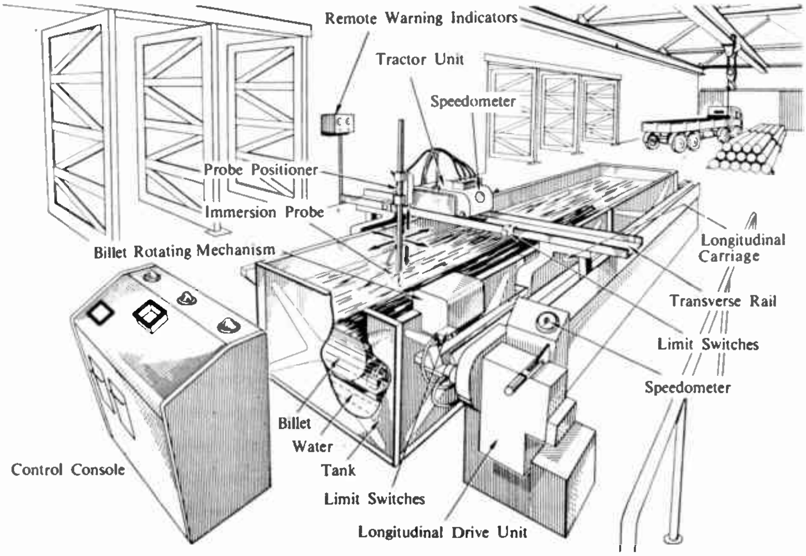


Fig. 18. Sketch of equipment to inspect bar material.

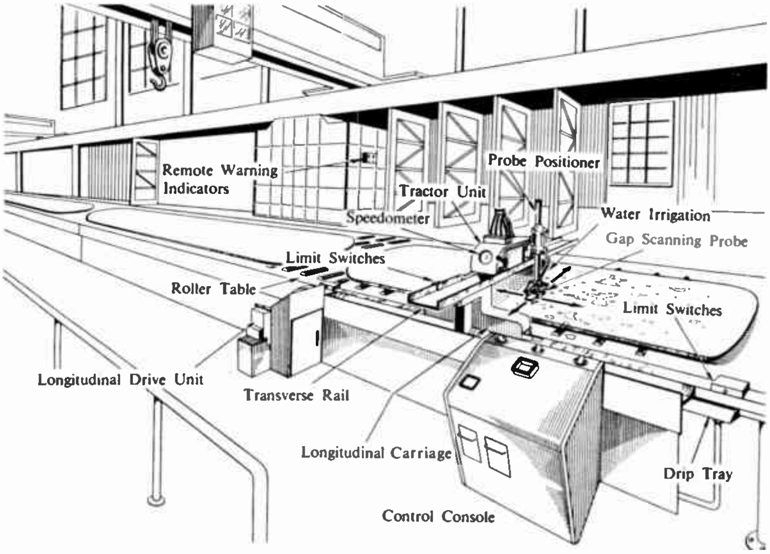


Fig. 20. Sketch of equipment to inspect plate material on the roller table of a mill.

Fig. 19. Gap scanning of plate material.

application under industrial conditions. It is certain that in the future all forms of non-destructive examination must be of the type which can be integrated into normal production schedules, as can the Autosonic equipment. In addition it is felt that non-destructive testing will change in character from just detecting the presence of discontinuities in material to monitoring continuously the quality of the product being produced by a given process. This second application opens up a potentially large field but one in which there is required much painstaking work to correlate variations in physical properties of the material under normal production conditions.

8. Bibliography

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2. G. Bradfield, "Improvements in ultrasonic flaw detection," *J.Brit.I.R.E.*, **14**, pp. 303-308, July 1954.

. . . Radio Engineering Overseas

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551.510.53

Solar eclipse of 30th June, 1954 and its effect upon the ionosphere. S. N. Mitra. *Indian Journal of Physics*, **31**, pp. 309-323, June 1957.

Experimental investigations to determine the effect of the total eclipse of the sun on 30.6.54 are described. The investigations were: (1) vertical incidence ionospheric measurements at Delhi, Srinagar and Bombay, (2) recording of the variation of short wave signals from the B.B.C. and Moscow at Delhi, (3) recording of field strength variation of medium wave signals from Jullunder at Delhi, (4) measurement of ionospheric absorption at vertical incidence using pulsed transmissions by means of an automatic absorption recorder at Delhi, and (5) recording of solar radio noise on 204 Mc/s at Delhi. The effect of the optical eclipse on the ionospheric layers could not be definitely established, due probably to the eclipse occurring around sunset when most of the optical effect was likely to be obscured. But evidence of three distinct "corpuscular eclipses" was obtained both on the ionization density of the F-layer and on the absorption in the non-deviating region. These were found to occur 2, 4 and 6½ hours before the optical eclipse. Theoretical arguments and past observations indicate that these corpuscular emissions may have originated from the so-called M-region of the sun.

551.510.53

Models of the lower ionosphere as may be inferred from absorption results. P. Bandyopadhyay. *Indian Journal of Physics*, **31**, pp. 297-308, June 1957.

Values of deviative and non-deviative absorption and their variations with cos α are calculated for some of the proposed D and E region models. The results obtained are compared with the available experimental data. It is found that so far as the E region is concerned, A. P. Mitra's theoretical model is most consistent with the observed diurnal variation of absorption. For the E region, the model, as proposed by Jones, is found to be unacceptable. Conditions which are to be satisfied by an acceptable E region model are discussed.

621.314.015.3.026.44

Transients in smoothing filters of high-power rectifiers. T. Konopinski. *Prace Instytutu Tele-i-Radiotechnicznego*, **1**, pp. 3-18, 1957.

Switching on of anode voltage in high-power rectifiers and rapid changes of load while keying give rise to overvoltages in rectifier filters which may cause damages in the components of the connected equipment and of the rectifier itself. The paper contains an analysis of transients in supply units with choke-input filters occurring on rapid application of anode voltage as well as during stepped variations of the load resistance. The formulae deduced permit the maximum values of overvoltages and overload currents to be determined.

621.314.7

Experimental determination of the base and emitter-lead resistances of alloyed junction transistors by means of low frequency measurements. W. Guggenbuhl and W. Wunderlin. *Archiv der Elektrischen Übertragung*, **11**, pp. 355-358, September 1957.

Starting from the basic equations of the one-dimensional theory of junction transistors, formulas for low-frequency parameters of a junction transistor with extrinsic lead resistances are presented. The lead resistances can then be calculated from the low frequency parameters (h-parameters). Experimental results for these base- and emitter-lead resistances determined by the above method are presented and compared with the corresponding values found by other methods. The practical validity of the one-dimensional equations for the low frequency behaviour of alloyed junction transistors is confirmed.

621.317.361.018.756

On error in measuring the frequency spectra of pulses by means of stagger tuned resonant circuits. G. Seeger and H. G. Stablein. *Archiv der Elektrischen Übertragung*, **11**, pp. 325-330, August 1957.

The method of directly measuring the frequency spectra of pulses by a system of stagger-tuned resonant circuits gains increasingly in importance. The dissipation factor of the circuits used causes errors, however, whose kind and magnitude are discussed. A quantitative assessment gives a survey of the frequency range over which the spectrum can be covered with a certain predetermined measuring accuracy. The investigations are carried out for two cases: circuits of equal absolute and relative bandwidths respectively. With a given admissible error a maximum frequency band can be covered in practice if the circuits are suitably stagger-tuned with respect to their bandwidth.

621.317.757:621.396.822

Errors in the noise spectrum analyser of heterodyne type. U. Taki and U. Takano. *Journal of Institute of Electrical Communication Engineers of Japan*, **40**, pp. 437-442, April 1957.

This article contains the general discussion on errors in the measurement of Gaussian noise by the spectrum analyser of heterodyne type. The frequency spectrums are measured, either continuously by sweeping the local oscillator frequency, or discretely by point-by-point method. Moreover, the noise under measurement may be analysed directly or recorded in tape to reproduce repeatedly for the analysis.

621.318.42:621.396.616.015.7

Magnetic pulse generator. M. Bednarek. *Prace Instytutu Tele-i-Radiotechnicznego*, **1**, pp. 47-70, 1957.

The principle of operation and an approximate mathematical analysis are presented of a pulse generator using coil with ferro-magnetic core; the generator operates in the range of saturation, with high degree of non-linearity. The analysis is based on the assumption of a broken-line characteristic consisting of three sections, instead of the hysteresis loop. The initial impulse appears on the resistance R of an RLC-circuit as a result of its discharge. This may be of damped-oscillatory or aperiodic type. Both cases have been considered in the analysis. General conclusions have been drawn as to possible application of this device as pulse generator and harmonic generator.

621.372.142

Formulae for characteristic frequencies of the dipole equivalent to a piezo-electric resonator. P. ANDRIEUX. *Onde Electrique*, **37**, pp. 746-749, September 1957.

A knowledge of the relations connecting the various characteristic frequencies of a crystal resonator is important both from a point of view of the measurement of these characteristics and the use of crystals in filters and oscillators. The various relations are given with sufficient degree of approximation to cover most needs. Terminology concerning the characteristic frequencies of a resonator is set in accordance with recent international specifications.

621.372.2

Surface wave propagation along coated wires. T. BERCELL. *Acta Technica (Budapest)*, **17**, pp. 219-250, 1957.

The dielectric loss of the coating decreases with the increase of the dielectric constant while its magnetic loss increases as the magnetic permeability increases. Dielectric loss depends also on magnetic permeability and magnetic loss on the dielectric constant.

The attenuation of a given transmission line has a minimum as the function of field concentration. This is the optimum field-concentration. In the designing of surface wave transmission lines, the purpose is to find and produce the optimum field concentration. Optimum field concentration may be produced with the use of a coating of adequate thickness.

621.373.5

Experimental and theoretical investigations of semiconductor Hall effect oscillators. M. J. O. STRUTT and S. F. SUN. *Archiv der Elektrischen Ubertragung*, **11**, pp. 261-265, February 1957.

A feedback circuit incorporating an indium antimonide pellet and a suitable magnetic circuit, containing ferrite core materials is described. At room temperature d.c. power amplification is achieved with this circuit. The theory is well confirmed by experiments. Based on these results, an oscillator circuit was designed. With this circuit, oscillations were obtained at room temperature in the frequency range 13 to 330 c/s. The experimental data accurately confirm the theory especially as regards the time-constants of starting oscillations. Experimental data is given on useful power outputs up to about 12 milliwatts. It is shown that this useful power output amounts to 22 per cent. of the power supplied to the oscillatory circuit. Most of the d.c. supply power is consumed in the ohmic losses of the semi-conductor pellet. The influence of temperature on the performance of the oscillator is discussed.

621.375.4

The junction transistor as a network element at low frequencies, II. Equivalent circuits and dependence of the *h* parameters on operating point. J. P. BEIJERSBERGEN, M. BEUN and J. TE WINKEL. *Philips Technical Review*, **19**, No. 3, pp. 98-105, September 1957.

To determine how a transistor behaves in a proposed circuit, an equivalent circuit suited to this circuit is chosen. The types most commonly used are mentioned. A so-called "physical" equivalent circuit is then derived in which the elements can easily be expressed in terms of the physical quantities governing transistor action. This equivalent circuit is used to investigate how the *h* parameters for the common-emitter configuration depend on the d.c. operating point (biasing) and on temperature. An appendix gives a detailed explanation of how the Early effect is allowed for in the physical equivalent circuit.

621.375.4

Transistor noise in the low frequency range. J. SCHUBERT. *Archiv der Elektrischen Ubertragung*, **11**, pp. 331-340, August 1957.

Measurements of the noise behaviour of transistors over a wide range of frequencies give evidence of the validity of a simple equivalent circuit in the region of white noise that indicates the analogy to the noise of a vacuum triode. It is shown that the equivalent circuit devised by Montgomery, Clarke and van der Ziel corresponds to this equivalent circuit. The optimum operating conditions for a minimum noise figure in the region of white noise are given for the grounded-emitter, grounded-base and grounded-collector circuits. For the region of excess noise it is shown which noise sources of the equivalent circuit supply the principal contribution to the excess noise. The noise parameters of the equivalent noise quadripole of a transistor are stated.

621.375.4:621.372.5.018.78

Theoretical and experimental examination of distortion in low frequency junction transistor quadripoles. G. A. SPESCHA and M. J. O. STRUTT. *Archiv der Elektrischen Übertragung*, **11**, pp. 307-320, August 1957.

The nonlinear distortions are treated on the basis of the equations of a non-linear quadripole in the hybrid form. The quasilinear hybrid parameters of the fourpole are extended by the addition of distortion expressions, which may be calculated by differentiation of the quasilinear parameters. It is shown that this extended representation fully describes the nonlinear quadripole within a definite range of control. For the calculation of output distortion a purely sinusoidal voltage source in series to a linear source resistance is connected at the input and a linear load resistance at the output. By means of the above distortion quantities the relative values of second and third harmonic distortion at the load terminals are calculated. The distortion parameters are determined experimentally.

These results are then applied to a junction transistor quadripole in the grounded base, grounded emitter and grounded collector connections. The methods of measuring the distortions are described fully. For the grounded base circuit the results of calculations and measurements of the second harmonic are compared and found to be in ample agreement. Attention is drawn to the existence of values of source and load resistance at which the second harmonic distortion at the output is zero. Similar results are obtained for the grounded emitter connection. In the grounded collector circuit the distortion values are relatively small and no calculations were made. The second harmonic at the output was determined experimentally. Finally, conclusions as to applications to amplifier stages are stated.

621.376

A new method of demodulation for phase, frequency and amplitude. P. KUNDU. *Indian Journal of Physics*, **31**, pp. 231-234, April 1957.

This paper describes a new method of demodulation of angle and amplitude modulated waves. The principle is based on the fact that the distance between the leading edges of the successive pulses obtained by properly limiting and then differentiating a modulated sinusoidal wave is a function of the instantaneous angle. It is also a function of amplitude of the modulated sinusoidal signal if the slicing level is above the zero axis. These variable distance pulses are then converted to variable amplitude sawtooth waves. The original modulating signal is finally obtained by passing the sawtooth wave through a low-pass filter.

621.383.27

Stroboscopic operation of photomultiplier tubes. C. F. HENDEE and W. B. BROWN. *Philips Technical Review*, **19**, pp. 58-58, 1957.

A photomultiplier tube supplied with pulsed dynode voltages acts as a light shutter, capable of an "on" time as short as 10^{-7} sec. A light flash which is periodically repeated can be analysed stroboscopically by synchronizing the flashes (of, say, 10^{-6} sec duration) with the phototube pulses in a constant, adjustable phase relation. Integration of the phototube collector current over a long period (e.g. 10 sec) and repeating the light flashes at a high rate (up to 10,000 per sec) results in accurate instantaneous intensity measurements, even with extremely low light intensities, e.g. after spectral dispersion by a monochromator. An important factor in the experiments is the extremely high gain attained with the phototube under pulsed operation (up to 10^6).

621.387.424

Development of a new gamma radiation meter. R. GUERTLER and R. G. MCCARTHY, *Proc. Instn Radio Engrs, Aust.*, **18**, pp. 359-362, October 1957.

The d.c. voltage of a 22½ V dry battery is converted to a high a.c. voltage at about 15 kc/s in a transistor oscillator; this is rectified by a selenium diode voltage doubler circuit, and stabilized at 345 volts by two neon tubes. This d.c. voltage supplies the high tension for a halogen-quenched Geiger-Müller tube and for a diode amplifier which uses two neon tubes to amplify the discharges in the G-M tube. A 0-50 microammeter is used to measure the average current drawn from the amplifier section, and thus to provide a rate-meter.

621.395.665.1

"Frena", a system of speech transmission at high noise levels. F. DE JAGER and J. A. GREEFKES. *Philips Technical Review*, **19**, No. 3, pp. 73-83, September 1957.

By transmitting the frequency component and amplitude component of speech in two separate channels—the former in a single-sideband channel of 3,000 c/s bandwidth and the latter in a channel say 100 c/s wide—it is possible to receive the speech in fairly intelligible form at very low signal-to-noise ratios. Communication is possible at a ratio of 8 db when the amplitude component is transmitted as an a.m. signal, at 6 db when it is transmitted as an f.m. signal, and at a ratio as low as 4 db if the amplitude component be simplified into a "pilot" signal that merely indicates at each instant whether a phoneme is present or not (the "Frena" system). That the degree of intelligibility is satisfactory at this very high noise level must be attributed to the fact that the noise is suppressed at precisely those instants when it is most troublesome.

621.396.619.24

Single-sideband, present and future. R. JEREMY. *Proc. Instn Radio Engrs Aust.*, **18**, pp. 363-371, October 1957.

The principles and advantages of s.s.b. operation are discussed, particularly from the point of view of civil ground-to-air communication. Some modern i.s.b. drive and transmitting equipments for use on long distance fixed circuits are described and the problems associated with the development of equipment to meet the needs of other services are discussed.

621.396.662

Some aspects of permeability tuning. W. D. MEEWEZEN. *Proc. Instn Radio Engrs Aust.*, **18**, pp. 263-275, August 1957.

In the first part of the paper, permeability-tuned circuits are analysed and compared with capacitance-tuned circuits. Attention has been given mainly to aerial circuits for the broadcast band. The second part of the paper deals with the construction of permeability tuners. The causes of law and tracking errors are discussed and an indication is given of the manner in which these errors can be reduced and corrected. Finally, a tuner is described. Not only does this feature an adjustable tuning law, but it also approaches the ideal linear frequency law more closely than do most of the commercially used tuning capacitors.

621.396.663

Phase distortion due to ground inhomogeneities. K. BAUR. *Nachrichtentechnische Zeitschrift*, **10**, pp. 385-389, August 1957.

Investigation of the direction-finding site takes up most of the work performed in setting up d.f. equipment. Special attention must be paid to any latent characteristics of the ground surface which express themselves in local fluctuations of the ground conductivity and of the dielectric constants. This condition causes a local phase deviation from the nominal value and thus false d.f. results will be obtained. Formulae have been derived which permit a definition of the ground quality for d.f. purposes and thus a criterion for selecting the d.f. site.

621.396.93

The assessment of reliability. T. R. W. BUSHBY. *Proc. Instn Radio Engrs Aust.*, **18**, pp. 276-284, August 1957.

A programme for the assessment of the reliability of airborne electronic equipment was instituted in 1948. The methods adopted in the collection, analysis, presentation and utilization of the data are described.

681.14:621.318.124

Magnetic switching circuits for the representation of logical relationships. H. GILLERT. *Nachrichtentechnische Zeitschrift*, **10**, pp. 391-402, August 1957.

Magnetic switching circuits are described which can be used for producing logical relationships by superposition of positive and negative magnetic fields of different amplitudes. The known AND and OR operations are special cases of a multitude of possible operations. The number of magnetic cores in a circuit and the number as well as type of turns on the individual cores for a given circuit function are derived from general design principles. A minimizing method leads from a given circuit function to a circuit with the smallest outlay. The limits of the reported method are investigated and stated. The results of a systematic investigation for a circuit function containing 2 and 3 variables are reported. A binary series-adding and series-subtracting network is given as an example.