JOURNAL OF

The British Institution of Radio Engineers

(FOUNDED IN 1925 - INCORPORATED IN 1932)

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

Vol. 16 No. 12 DECEMBER, 1956

DEFINING AUTOMATION

In June 1956, when members received their first intimation* that the subject of the 1957 Convention is to be "Electronics in Automation," the American periodical *Electronics* published the following definition of automation:

> "The technique of improving human productivity in the processing of materials, energy and information by utilizing in various degrees elements of self-control and of automatically executed product programming,"

the authors of this definition being the Radio, Electronics and Television Manufacturers' Association of America.

Now, whilst it can often be said that a subject has become sterile when it reaches the stage in which experts are prepared to waste time discussing definitions when they might be better occupied in research, it is worth considering if this is true of automation and in particular whether the above definition is valid.

The first notion which has to be dispelled is that automation is a new thing. Certainly by the above definition this is not so, and the wheel gives an example so ancient as to have its invention lost in pre-history. Coming to more recent times, the spinning jenny and Jacquard loom date from the eighteenth century, and the capstan and automatic lathes from the nineteenth. If more evidence is needed, it is necessary only to remark that automatic data processing was clearly envisaged by Babbage in the 1830s, and that the first practical punched card installation was produced by Herman Hollerith in the 1880s.

These examples show that our subject is ancient and readers may be wondering: firstly, why so much interest exists at the present time, and secondly, is our Convention justified?

To the first of these questions there is a simple answer, but one which is not strictly within the province of the engineer. It lies in an examination of the sociological and political scene as it existed at the end of the second world war, and as it had been developing since the end of the first. Without entering into contentious argument, the situation may be described as the desire of the worker to do less and less for more and more, coupled with a realization by the more intelligent elements of our society that economic survival could result only from an offsetting of this trend by an increasing use of automatic methods.

For an answer to the second of our questions we need refer only to the last phrase of the previous paragraph, and to the objective of the Institution as expressed at the head of this page. If more is needed, a consideration of the enthusiasm with which the discussion on Automation at the 1956 British Association meeting was received gives a clear indication of general desire, whilst at the same time revealing the need for an opportunity for the exchange of ideas on a more technical plane than was then possible.

What then of the definition? Certainly it fits those few facts which it has been possible to cite here and, at least superficially, it accords with the general corpus of knowledge. From the offers of papers for the Convention so far received, it is clear that active research *is* still being carried out in the field of automation. It is hoped that many more papers will follow and thus give justification to a refusal either to argue the detailed validity of the present definition or to attempt another.

A. D. B.

* "The 1957 Convention," *J.Brit.I.R.E.*, **16**, p. 297, June 1956.

NOTICES

New Format of the *Journal*

As announced in the Annual Report, the January issue of the *Journal* will include a full colour reproduction of the Institution's Armorial Bearings, together with a heraldic and general description. The cover has been redesigned to to incorporate the Coat of Arms, and a number of alterations have been made in the format and to the typographical lay-out, with the object of improving readability and appearance. One change is that the contents list, instead of being on the cover, will be given on an inside page. The distinctive pale blue cover is however being retained.

Other contents of the January issue will include the Presidential Address of Mr. George A. Marriott, the fifth of the Technical Committee's Reports on Materials Used in Radio and Electronic Engineering—Electrodeposition of Metals, and papers on Analogue Computers, Travelling Wave Tubes, and the Electronic Circuitry of a Balancing Machine.

Completion of Volume

This issue completes Volume 16 of the *Journal*. An index to the Volume will be distributed with the January 1957 issue.

Members wishing to have their *Journals* bound by the Institution should send the complete set of issues and index to the Institution together with a remittance of 12s. 6d.

Inaugural Meeting of the South Midlands Section

The establishment of a South Midlands Section holding meetings alternately at Cheltenham and Malvern was authorized by the Council during the summer, and the inaugural meeting of the Section was held on 5th October at the North Gloucestershire Technical College, Cheltenham.

The Chairman, Mr. D. L. Leete,* introduced Professor Emrys Williams, who brought greetings from the General Council and from the South Wales Section. A paper was then given by Mr. A. E. Robertson, Assistant Head of the B.B.C.'s Engineering Training Department at Evesham, on "Television Lighting Effects." He dealt with both the technical and artistic aspects of lighting for monochrome television, and also referred to the special problems which arose with colour television. His paper was accompanied by comprehensive demonstrations.

* See page 679 of this issue.

Preparations for the I.G.Y.

The scope of the investigations into radio, meteorological and magnetic phenomena to be carried out during the International Geophysical Year were referred to in an editorial in the May 1955 *Journal*. The I.G.Y. starts next July and extends until December 1958, and preparations are now well in hand for setting up research stations in various parts of the world.

During November, the Royal Society's Antarctic Expedition left London for its base at Halley Bay (75°31′ S, 26°36′ W) and its equipment includes ionospheric sounding equipment and wind-finding radar. Most of the investigations will be related to the variations in activity of the E and D layers of the ionosphere and their correlation with magnetic and auroral activity; atmospheric noise at low radio frequencies (below 500 kc/s) will also be studied. Observations of radio star scintillations will be made using 60 Mc/s equipment. One of the members of the ionospheric group is Mr. L. W. Barclay, a Graduate of the Institution, who has been a research engineer with E. K. Cole Ltd.

Institution members are also participating in other Antarctic expeditions, and the New Zealand second-year party at Scott Base in the Ross Dependency will be led by Mr. L. H. Martin (Associate Member). With six colleagues, he will be in Antarctica from December 1956 to March 1957, and again from December 1957 until the final withdrawal of the I.G.Y. parties early in 1959. Mr. Martin, who serves on the Committee of the Wellington Section, is with the New Zealand Broadcasting Service and contributed a paper to the *Journal* in 1953 on ionospheric disturbance forecasting.

Robert Blair Fellowships

Applications are invited for the 1957 Robert Blair Fellowships in Applied Science and Technology. These applications should be made to the Education Officer of the London County Council before the 28th February 1957.

The Fellowships are open to candidates who are British born subjects and at least 21 years of age and who have been trained in Applied Science and Technology.

Preference will be given to candidates who are qualified in engineering science and to those who have completed a course of study in a London institution.

INDUSTRIAL DATA-REDUCTION AND ANALOGUE–DIGITAL CONVERSION EQUIPMENT *

by

P. Partos †

SUMMARY

Representative examples of specifications for data-reduction systems are presented and the data-reduction system considered as a tool which can meet the wide variety of practical requirements. The central elements of the system are analogue–digital converters which are described in detail. Existing and proposed installations are reviewed in two main groups: electro-mechanical and electro-optical devices, and pure electronic converters. Only the main features of the other major elements of the system—input devices, programmers, alarm detectors and digital output devices—are discussed. The probable trend of future development is outlined.

TABLE OF CONTENTS

1. Historical Introduction

Recent social and technical discussions around the concept and the reality of "Automation" have focused interest on the industrial applications of new electronic techniques. The real history of these developments is at first sight fairly short. The first papers on analogue–digital converters were published in 1948, and the first references to systems designed to process and handle digital data in 1950. However, in retrospect, the rapid progress of these last seven years may be seen as the logical outcome of two parallel lines of development: the growth of the modern industrial process plant outstripping the potential of conventional instrumentation and control, and the rapid development of new electronic techniques, mainly from the impulse of military needs, which created new means of solving the industrial problems. Jointly these two developments have lead to the techniques of "data-reduction," which together with digital computers, machine control, mechanical handling, and automatic process control are essential parts of "automation."

The tools of data-reduction are as yet too little tried and too much subject to further development to allow for a balanced final judgment of their capabilities and merits. However, enough has been solidly accomplished to date to form the basis of a report on "work in progress."

* Manuscript received 7th August 1956. (Paper No. 377.)

† Panellit Ltd., Stanmore, Middlesex. (Formerly Elliott Bros. (London) Ltd.)

U.D.C. No. 621.398:621.374.32.

Industrial requirements have outgrown the conventional means of instrumentation and data handling in three directions: size, speed and character.

The large industrial plant of recent construction, chemical and oil plant, iron and steel manufacture, power stations, rolling mills, etc., present new problems of plant control and management. Not many years ago, descriptions of new plant control rooms referred with some pride of achievement to the hundreds of feet of control panels or the many hundreds of indicating or recording instruments. It soon became evident however that it is difficult, if not impossible, for the operators to gain a clear picture of the state and changes of the manufacturing process through observing hundreds of instruments and singling out the relevant ones from the dispersed mass of irrelevant data. Log sheets on which "loggers" record periodically the data become unrepresentative because of the long lag between reading the instruments from first to last, and their interpretation so long a task, that the information has lost its usefulness by the time it becomes available.

Instrument miniaturization, "graphic" panels which present the information semi-pictorially in a flow-diagram of the plant, were the first palliatives devised to enable the human operator to retain control of the process by direct observation. This is the prevailing method of control in fairly recent or recently modernized plant; but it has an inherent limit in the capacity of the human operator, and this limit is exceeded by the continuing growth of plant both in size and complexity. Hence the need for a new technique which can bring all relevant data simultaneously together on a single sheet, and which can "reduce" data by omitting irrelevant information and bringing out the essentials.

In the ordinary running of large process plants, power stations, etc., changes are slow and speed of record is not very important. This is, however, only true when the plant is well known and long experience has built up enough knowledge to make efficient control possible. When a new plant is commissioned, or existing plant turned to new or unusual conditions, it is of great importance to obtain data on the plant characteristics, and the short and long term effects of change in any one parameter on all the others. The more accurately, more frequently and more instantaneously readings can be taken on all measuring points, the easier it will be to establish empirically the dynamic characteristics of the plant and formulate best control action. The manual logging of conventional instrument readings is obviously inadequate here. A number of strip chart records may give the information, but on a compressed time scale and with only very approximate synchronization of the different charts.

In another field of application, the performance of aero-engines or car engines, stress studies of aircraft structures in wind-tunnels, etc., speeds of a quite different order become essential. Changes of important conditions may take place here in seconds and simultaneous information on a great number of parameters at high repetition rate is imperative. Conventional instrumentation cannot begin to satisfy these requirements.

In the third aspect, character of the information, the introduction of digital computers into industry has created a new type of requirement: the translation of inputs into digital form. The operational computer requires a high number of digital data, derived from primary information normally reproduced on indicators, meters and recorders. Even the business-type computer requires a certain amount of data on plant inputs and outputs normally registered on analogue instruments. In most cases, the task of manually converting the information into digital forms would be quite impossible.

The technical conditions for the new techniques are those which have produced computers, radar, etc. J. F. Coales[1] has recently given the credit for the new "Industrial Revolution" to the development of servo-mechanisms and pulse techniques. They certainly deserve pride of place, but other parallel developments such as d.c. amplifier techniques, the development of new electro-mechanical components capable of working on very low signal levels, and a range of transducers to convert physical data accurately into electrical information, should be added as other basic elements. Also, it would not be too far fetched to say that the recent developments in the field of information theory, together with mathematical progress in the fields of matrix theory, transforms, and non-linear network analysis have all been less visible, but essential contributors to the present developments in data handling.

2. Representative Requirement Specifications

Data-reduction is still too recent to permit the formulation of one or two specifications which can be applicable to all requirements. Every industry, every plant even in the same industry, seems to present some special problem involving the design of equipment tailored to meet the specific requirements. The main reason for this may be that too little is known in industry about the potentialities of the technique, and this retards the knowledgeable formulation of requirements. However, from the available limited experience some common trends emerge, and can be used as pointers towards the design of standardized equipment.

In the following sections, four typical installations (two in the United Kingdom and two in the U.S.A.) will be described as an illustration. Table 1 shows the principal features in them side by side. They will serve as reference to the elements of the system which will be discussed subsequently.

2.1. *Large Power Station (U.S.)*

This is a large power station supplied from natural gas, and providing electrical output with a maximum capacity of 410 megawatts. For a complete monitoring of the plant, the following information must be checked at frequent intervals:—

Table 1

Representative Data-reduction Specifications

	Power Station	Chemical Plant	Aero Test Bed	Weighing Installation
Number of input points	192	48	350	6
Points to be logged	92	48	350	6
Additional points computed	8	1	12	6–12
Alarm points	100	45	—	—
Input levels (full scale)	<10 mV	<10 mV	<4 mV	<10 mV
Non-linear inputs	Thermocouples, flow square-root-laws	Thermocouples, flow square-root-laws	Thermocouples, flow square-root-laws	—
Resolution	1000 parts	1000 parts	Up to 10,000 parts	200 parts
Accuracy	<1%	<1%	<0·1%	<1%
Scales of variables	Various, individually calibrated	Various, individually calibrated	Various, individually calibrated	All common scale
Logging rate, normal	Hourly	Hourly	One every 5 min.	Sequence controlled
Deviation scan and log	Continuous	Every 5 min.	None	None
Logging time per point	1–2 sec.	1–2 sec.	1 sec.	5–7 sec.
Deviation scanning rate	5 points per sec.	2 points per sec.	—	—
Type of record	Automatic typewriter	Automatic typewriter	Punched tape	Automatic typewriter

(1) Flows of natural gas input, and feed water	14 points
(2) Pressures of steam, oil, water and gas at different stages of the process	39 ,,
(3) Levels of water tanks	2 ,,
(4) Conductivities of boiler water and condensate	11 ,,
(5) pH of feed water	4 ,,
(6) Power output	10 ,,
(7) Temperatures of gas cooling, oil cooling, superheater and reheater	12 ,,
(8) Temperatures of generator bearings	100 ,,

With the exception of the last item, a total of 92 points is required as quantitative information to accuracies of 0·1 per cent. In the last item, temperature of bearings, the only important information is whether the safe value is exceeded. The requirement, therefore, is for digital logging of the variables on the first 92 points, and alarm detection on the 100 bearing temperature points.

Further, the information of flow rates must be integrated and in some cases averaged to obtain total and average flow. Similarly, the kilowatt output rate must be integrated for the total kilowatt-hour production. Efficiency must be calculated constantly, from the ratio of fuel input to kilowatt output.

A number of the measurements, involving particularly pressures and flows, are affected by temperatures and pressures at the measuring point. In order to gain information of true values, measured values have to be corrected for the prevalent temperature and pressure.

When the station is operating normally, an hourly log of each variable is sufficient for recording, accounting and statistical purposes. However, the plant may be subject to disturbances, due to imperfect control, breakdowns etc. The installation, therefore, must monitor all the measuring points more or less continuously, and provide alarm indication and a logged record at any time when any one or more points deviate from the normal band of readings. Should such disturbance occur it is of interest to get as complete a picture of the disturbance as possible. Apart from the digital logged records, which provide regular logs at hourly intervals, and a logged record of any deviation from any point, a small group of trend recorders must be made available, which may be switched on to any section of the measuring points for continuous pen record, either manually or automatically, as soon as a disturbance is observed.

2.2. *Chemical Industry Distillation Plant (British)*

Automatic instrumentation of two sections in a major continuous process chemical plant covers the same types of primary measurements: flow, pressure, level and temperature. The flow rates of the chemicals involved in the process and of steam in the heat exchanger are measured at 10 points. Gas pressures are checked at 7 points. Feed tank levels are monitored at 6 points. The temperatures on the different levels of the distillation columns are measured at 25 points. A total of 48 measuring points is covered, and each point must be logged automatically for record purposes every hour. The log must also be available on demand any time (for instance the beginning of new working shifts) and, in addition, the plant must be monitored at 5-minute intervals for any deviation from set-point levels. Deviations are recorded and must operate an alarm signal.

2.3. *Aero-dynamics Testing Installation*

Air frames and engines of high performance aircraft are tested in wind tunnels and pressurized chambers, both in experimental stages to establish best designs and in production testing. Tests are, of necessity, of short duration and the changes of variables occur at very high speeds. The quantities measured are again of similar order: temperatures of bearings, fuel burning, etc., flows of fuel, air and oil, pressures of fuel, oil and air, and work output measurements of torque or thrust. The number of measuring points varies from installation to installation, being usually between 50 and 400; one American installation of this type is in construction now for over 2,000 points.

A particular installation of this type, with about 350 measuring points, calls for accuracies of better than 0·1 per cent. in the majority of the input points, and scanning rates at less than 1 minute intervals for the total of 350 points, i.e., 6–10 points per second. No set-point comparison and alarm facilities are required. The information is logged on magnetic or punched tape for subsequent use in a digital computer.

2.4. *Automatic Digital Weighing Installations* (*U.K.*)

This installation is used in unloading of cargoes by cranes. A battery of cranes (usually 5 to 6) takes successive loads out of a ship's holds, and discharges them into wagons, barges or lorries. An accurate digital record of the nett weight being unloaded in each crane movement is required, together with cumulative totals of the discharges, both in respect of the total amount unloaded from a particular cargo, and the sub-totals of that load transferred to a specific fleet of barges, lorries or wagons. The rate of information covered is much slower than the previous cases discussed, with each individual crane unloading operation taking up periods of the order of 1 minute. However, the record is complicated by the fact that there is no pre-determined sequence of operations, and that more than one individual load may be recorded on one of the primary measuring devices—electric load cells—simultaneously. A further complication is introduced by the fact that the individual crane control points are not easily accessible, and not well suited to house complex control equipment, so that the information must be transmitted to a remote centre point where recording and controlling takes place.

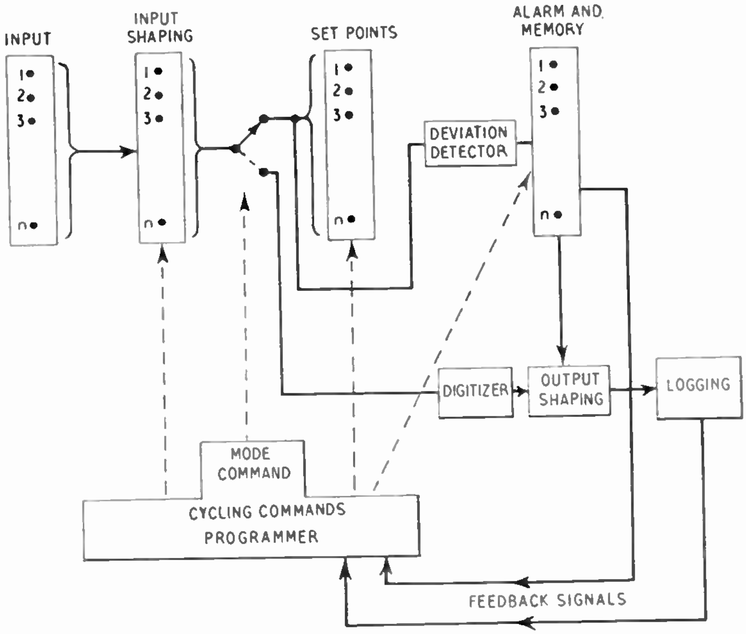


Fig. 1.—Block diagram of a complete Data-Reduction System.

3. The Integrated Data-reduction System

The general functions and the make-up of Data-Reduction systems have been described by various authors.[2-5] The descriptions vary slightly according to the particular methods and techniques employed by the authors, and the following definitions follow the presentation given by Laws[2] and Sperry[5] as the author's work was most closely associated with them.

The block diagram of a system in Fig. 1 shows the major elements of a system and their inter-relation. The input information is received in some input units where they are first transduced into terms acceptable to the digitizer and/or deviation detector, calibrated in terms of the digital output, in some cases linearized, and provided for any other special features such as "suppressed zero" scale, etc.

There is one input shaping element for each input, though in some cases certain provisions may be shared between a group of homogeneous input points. For instance, thermocouple inputs of the same junction type may in suitable cases share a common cold-junction compensating circuit.

Where there is a deviation-detection requirement, each such point is also provided with means for setting up the high or low limits, or both.

The programmer shown in the lower half of the diagram provides the automatic sequence of events. It has two major functions; one is to initiate the commands which determine the mode of operation, and the other is to supervise and progress the correct cycle within each mode.

There is usually more than one mode of normal operation. There may be logging cycles at fixed time intervals, deviation detecting cycles at other fixed intervals, or continuously. Either cycle may have to be initiated by manual command, or sequence-controlled, i.e. as a consequence of some event occurring, or the completion of some process. Some mode of operation may need priority and over-ride any other simultaneous commands. The programmer must be shaped to cover these requirements.

Once the mode of operation is settled and a cycle started, the further duty of the programmer is to sequence the cycle through. It must switch each relevant point successively into the cycle, again either controlled by a fixed time interval, or sequentially, i.e. the completion of one point determining the start of the next one. The different "feedback" lines on the diagram supply the information on the completion of an operation to the programmer and enable it to progress forward on the cycle.

The remaining blocks of the diagram represent elements of which there is normally only one per equipment. Their basic function is self-explanatory. Deviation detectors, operating the alarm provision for each point, digitizer and output logger complete the functions, in the form of suitable records and deviation alarms. Some idea of the complete system may be gained from Fig. 2, which shows a representative data-reduction unit, with a capacity of up to 200 points.

These major elements of the system will be discussed in detail in the following sections. The digitizer will be considered first, not only because it is the heart of the data-logging work, but also because the choice of the digitizer—or by its fuller name the "analogue–digital converter"—has strong repercussions on all the other elements and the general performance of the system.

In some cases there may be other elements included in the system which are not shown in this general diagram. Some simple or more complex computing operations may be required, such as integration, totalizing, averaging, or possibly the calculation of some further quantity which is a function of one or more input measurement. These will be briefly discussed in Section 5.5.

It may be of interest to compare the data-reduction equipment as discussed here, say in the example of Section 2.2, with the conventional methods of instrumentation and recording which were employed in similar plants up to the present. The 48 measuring points would be covered probably by 2 multi-point recorders, 3 individual recorders, 1 multi-point indicator, 8 other instruments or gauges and approximately 30 safety alarms. In addition an operator would be required to take record on a manual log sheet at hourly intervals.

Data-reduction equipment therefore justifies itself economically as the comparatively high cost of basic digitizing recording equipment is at least compensated by the large number of instruments and recorders which it replaces and the saving of manpower. The upgrading of information in accuracy and in the common time scale of measurement (a manual log of 50 variables) are additional benefits. On the other hand any breakdown or failure affects only one measurement in the conventional instrumentation while in the data-reduction method it could conceivably immobilize all plant information. It is therefore necessary to provide a certain amount of standby instrumentation; hence, on the score of direct economics, the balance has to be drawn from case to case taking into due consideration the characteristics of the plant and the possible disastrous effect of any gap in the flow of information.

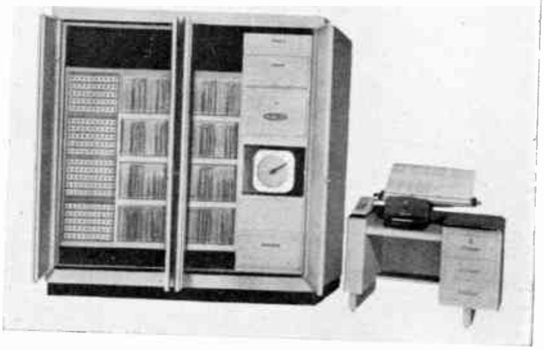


Fig. 2.—Standard Data-Reduction equipment with 200 point capacity (Panellit 605 system).

In view of the complexity of the data-reduction system the observed reliability is surprisingly high. This is largely due to the fact that the weakest element in electronic equipment, the thermionic valve, is only barely represented. In a full scale installation there are only approximately twelve valves (at any rate in units using electro-mechanical analogue–digital converters). The principal source of possible life trouble comes from the different switching elements. In these, present standards of reliability do not give complete safeguards against breakdown even with conservative circuitry and the highest grade available components. Further reference to this will be made in the Conclusions.

4. Analogue-Digital Converters

The first papers on analogue–digital converters were published around 1947 to 1949 and were in the main concerned with telemetry applications.[6-10] A general review[11] prepared in 1954 lists 41 different types of standard converters developed in the U.S.A. only; of these 34 are commercially available. These figures illustrate the rate of development in this field.

Several reviews of the existing approaches have been published in the last two years.[12-14] Different classifications of the available types are found in these reports, according to the type of inputs, speed of operation, methods employed, etc. We have chosen to divide the field into two main groups: (1) electro-mechanical and electro-optical devices, and (2) electronic devices.

The choice is guided by pragmatic considerations: all the devices in group (1) employ moving parts and are, therefore, comparatively limited in operational speed by the friction and inertia of moving parts. Group (2) devices are basically high-speed digitizers involving more complex and costly equipment. Since in industrial installations simplicity, ruggedness and low cost are important considerations, and moderate speeds are often sufficient, devices in group (1) have been generally preferred and further developed, and at present there is no known major industrial installation using a purely electronic analogue-digital converter. The trend of development suggests, however, that requirements will more and more often exceed the theoretical capacity of group (1) systems, and work on electronic devices is actively pursued.

4.1. *Electro-mechanical and Electro-optical Devices*

Four fundamentally different techniques fall under this heading. The first three have as common denominator the property that they convert into digits the position of a rotating shaft. They require, therefore, the conversion of all variable inputs into a shaft position. This is invariably achieved by a self-balancing bridge servomechanism, and the properties of this bridge servo have an important bearing on the overall performance. These servos are nowadays almost universal in industrial instrumentation. They consist of a servo-motor geared to a shaft on which a precision potentiometer or slide wire is mounted. The simplified circuit of the self-balancing bridge is shown in Fig. 3. The input voltage is compared with the voltage on the potentiometer slider in an amplifier. Any error voltage will cause the servo-motor to turn in the appropriate direction until the slider voltage is identical with the input voltage. By means of adjusting R_{cal}, the voltage across the slide-wire R_v can be adjusted to correspond to the full scale of the variable voltage. The bridge may be zeroed or zero offset if necessary by the pre-set control R_0. The bridge can be energized from a.c. or d.c. sources to suit the type of input signal.

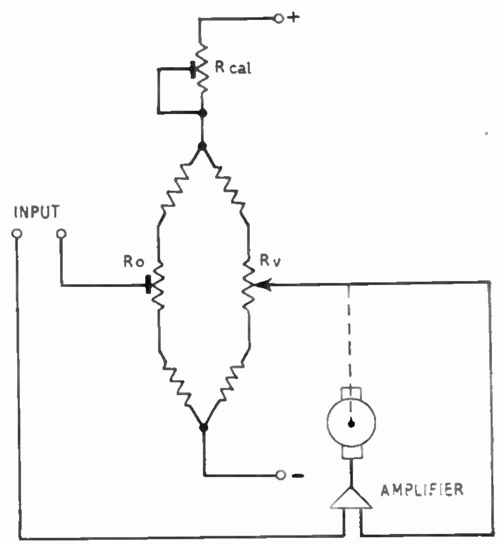


Fig. 3.—Simplified self-balancing bridge circuit.

Typical performance figures of available self-balancing bridges give full scale rotation of the slider by the servo-motor at best around 1 sec, with a servo discrimination (i.e. sufficient error signal to cause the servo-motor to turn and correct the error) of the order of 0·1 per cent. of full-scale deflection. The total scale varies between 300 and 336 deg. of shaft rotation, according to the type of slide wire, or precision potentiometer used. Slide wire linearity is of the order of 0·1 per cent. Signal-noise ratios of the combined bridge and amplifier are such that minimum full-scale deflections are on standard type bridges at about 10 mV d.c. (or 50 c/s a.c.). Special models have been produced to give full-scale slide wire travel for 1 mV input signal, but they usually require elaborate standardization and do not exhibit very good long term stability.

4.1.1. Geared mechanical switches

This is the simplest way of obtaining digital information on the position of a rotating shaft. The rotating shaft is coupled, directly or through a suitable gear, to the moving arm of a switch which has as many positions round the circle as the highest unit in the digital system employed. In a normal decimal system, for instance, 10 switch positions would be placed round the circle corresponding to numbers 0–9 in the most relevant digit. Geared down from the shaft in 10:1 ratio is an identical switch again giving the nearest relevant digit, and so on to the number of digits required in the digital answer.

With a potentiometer of limited angular rotation, say 300 deg. or 336 deg., the most relevant digit of the coupled shaft digitizer has to be geared to the shaft in a suitable ratio, so that the switch contacts effectively divide the rotation angle of the potentiometer.

The most direct experimental realization of this type of digitizer is described by Hampton.[15]

There is an obvious difficulty in the co-ordination of geared switches at the time when digits of higher significance change. Unless there is zero tolerance in the manufacture of switch contacts, brushes, gear box and overall assembly, the three switches will not operate simultaneously when the reading changes from say, "099 to 100." Suppose, for instance, that the "ten" and "hundred" switches each lag behind the "unit" switch by a very small fraction, there will be two intermediate false readings during the change-over; first "090", then "000' before finally the correct reading "100" is reached. A false reading is more dangerous when producing unchecked records than an obvious and complete breakdown. This "ambiguity" must be eliminated from any practical switch digitizer. The simple solution of spring loading the switch so that it positively jumps from one digit to another imposes unacceptable loads on the input shaft. Hampton solves the difficulty by a simple device involving double brushes on the higher digits, one leading and one lagging. When the last significant figure changes, it automatically controls a change from lagging to leading brush. This ensures a non-ambiguous transition of digits.

British experimenters, and some American commercial designs have used standard commutator and brush assemblies for the digitizer. Even with special precautions of finishes, low friction and inertia, and even at low operating speeds this must lead to short contact life.

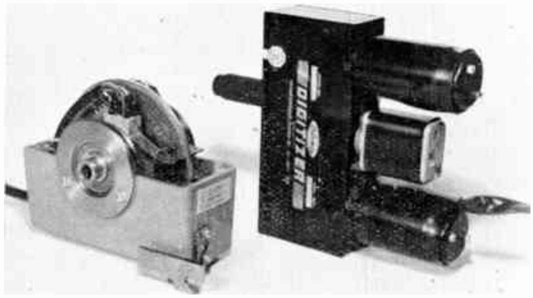


Fig. 4.—Standard analogue-to-digital converters. On the right is the Coleman shaft decade switch digitizer, and on the left the Giannini shaft encoder with the lid removed to show disk and brush assembly.

One American design, the "Coleman" digitizer, shown in Fig. 4, has overcome this difficulty and produced a device which was successfully used in data-reduction equipment in the U.S. and is fitted in one major British installation. Here the brushes are removed from the contactors while the shaft rotates, by means of solenoids, which may be seen in the two cylinders on the upper part of the illustration. This produces first of all very light shaft load (of the order of 0·01 oz-in.) and thereby makes high-speed bridge balancing possible. At the required read-out time the solenoids are de-energized by a pulse, and make momentary contact between brush and switch plate. The read-out figures are immediately stored elsewhere, in relays or other similar stores and the brushes removed again.

The "Coleman" digitizer also uses a double-brush system, and the least significant figure dictates the selection between leading and lagging brushes. Selection is done by a small high-speed relay which is mounted between the two solenoids.

Another American design developed by the Minnesota Electronics Corporation overcomes the friction problems by using magnetic switching. The digits are represented by magnetization of small magnetic drums which rotate with the input shaft, and the brushes are replaced by stationary reading heads. The actual performance of production models of this design is not yet known.

The speed of decade switch-type digitizers will be governed by the speed limitations of the switch itself. The best times are achieved by the "Coleman" type, where the solenoid pulse of a few milliseconds is the only time lag imposed so that conversion time is approximately the same as the bridge balancing time on the input shaft.

4.1.2. Shaft digital encoders

An alternative method to obtain by electrical switching a digital datum from a shaft rotation is to mount on the rotating shaft a number of switches and brushes. Each switch is made up of make and break sections of different length extending over the relevant part of the shaft rotation. Each switch can, therefore, convey on each point of the shaft rotation a "binary" information: it is either "on" or "off" at that particular point. For example, the first switch may be making for the first half of the rotation, and breaking for the second half. The second switch may be making in the first and third quarter, and breaking in the second and last quarter. Denoting making of the switch by "1" and breaking by "0", these two switches would "digitize" the shaft rotation in 4 parts: "11" for the first quarter, "10" for the second, "01" for the third, and "00" for the fourth. A third switch making on the odd eights and breaking on the evens would bring the discrimination up to eight parts, and so on, each additional switch being theoretically capable of raising the digitizing discrimination by a power of two. Seven switch segments can supply a discrimination of 128 parts, i.e. somewhat better than two figure accuracy, and 10 switch segments 1024 parts, i.e. 3 figure accuracy.

Practical shaft position encoders differ from the one described here only in one respect: the use of a "cyclic progressive" code to avoid ambiguity. The danger of ambiguity arises in the same way as in the mechanical switches of Section 4.2.

This danger can be removed quite simply. If in our simple four-part digitizer, the second switch is arranged to break in the first quarter and make in the second, but left unchanged in the second half, the digital answer for the four quarters will now be as follows:—10 11 01 00. It may be seen that at the mid-point only the first switch changes now. Therefore, a small misalignment in the switch system will only advance the time of change-over of the digits by a very small fraction, but can in no position produce incorrect digits. The same condition arises at all the other digit changes and would exist between the last and first digit if this cycle would be repeated at the end of the first one.

This alteration of code to avoid ambiguity is called the "cyclic progressive" code. It consists of the reversal of the make and break portions of alternate sections. If the above simple rule is carried on, for instance, in all the odd sections of each switch of a 1024 part binary shaft digital encoder, the table of resulting switch codes shows that in each change of digit only one switch has altered its contact arrangement. Therefore, if the accuracy of the total brush and switch assembly can be kept within limits of better than one digit, the accuracy of the total assembly will be better than the last significant digit.

When the analogue-to-digital conversion is used in combination with a digital computer, an answer in the binary code is the most suitable form for direct input into the computer. However, the true binary code as used in normal digital computing has been deliberately distorted by the "cyclic progressive" code in which the binary quantity of significance of each segment has been reversed in alternate portions. Some simple decoding arrangement is, therefore, necessary to give the answer in true digital values. This is normally done by means of a system of relays which are so interlocked that they give in their output contact combinations the same answer in the even sections of each switch, but invert the 0's and 1's in the odd sections.

Where digitizers are employed for straight logging, digital display or other direct forms of application, an output in binary numbers is not convenient as it would require either difficult mental interpretation or rather complex equipment to convert mechanically the binary figure into a straight decimal. A simpler means exists to obtain the digital answer in straight decimals by dividing the complete shaft rotation into decimal parts and "binarize" each decimal part in turn. The make-break combinations of four switches can discriminate between sixteen different parts. By using only ten of these sixteen possible combinations and associating each used combination with a digit, the four switches used may give a direct digital answer from 0 to 9. For a three-digit accuracy we require, therefore, a total of twelve switches as against the ten of the pure binary code. The use of a higher number of switches is, however, amply justified by the advantage of obtaining the answer in direct decimal digits.

With the high degree of redundancy available in the four-switch presentation of a decimal digit, there are a number of possible arrangements which exhibit the "cyclic progressive" characteristic. The choice among these combinations is largely arbitrary, though some advantages of simplicity and greater ease of manufacture are claimed for some particular codes. Two codes, the one used on the Giannini encoder[19] and that of the R.A.E. disk[16,17] are compared in Table 2.

Table 2

Cyclic Binary Coding of Decimal Digits

Digit	Giannini	Farnborough
	→	←
0	1000	0101
1	1100	0001
2	0100	0011
3	0110	0010
4	0010	0110
5	0011	1110
6	0111	1010
7	0101	1011
8	1101	1001
9	1001	1101
0	1000	0101

Note.—Arrows show direction of increase. Neither code employs the combinations "0000" or "1111" for any digit. This gives a check against the most obvious failures.

It may be seen that this method is equally applicable to systems which are not on the decimal basis. By suitable arrangement of the switches, the shaft encoder may deliver its output in £ s. d. units, by having its lowest significant figure digitized in twelve parts, the next step in twenty parts, and decimal units thereafter. Similarly, for other applications, weights may be expressed in tons, hundredweights, pounds or ounces or a system of 12 and 60 units may be used for a digital clock. Also, in any application, where the shaft rotation corresponds at its full scale deflection to a given quantity which is not a full decimal digit, say for instance, 800° F, the shaft encoding may cover only 0–8 in its most significant figure. These advantages are only obtainable, however, where the digitizer is used only for one particular type of input, having always the same full-scale range.

Shaft digital encoders operating in decimal or other arbitrary scales must be followed by a translator which interprets the switch combinations in terms of the final digits. These usually consist of one relay for every one of the digitizing switches. The relay switch combinations are wired in series so that each combination of breaks and makes closes the circuit—and only the circuit—of the appropriate digit. One such arrangement is shown in Fig. 5, translating one digit of a cyclic progressive decimal code (the Giannini code shown in Table 2) into decimal digits.

The translator may consist of self-locking relays, which hold the information, once read out from the shaft digitizer. This is usually necessary, as the input information may change during the process. If the shaft moves sufficiently to cause a change of at least one digit, further processing of the information may be confused or made incorrect by the presence of two different digits, or, even worse, the uncertain transition period between two digits.

Switch and brush assemblies giving a digital code pattern output are now commercially available in the U.S. and several British firms have announced that they will have similar or identical devices available in production in the near future. The best known American disk, the "Giannini" type, shown on the lower half of Fig. 4, is manufactured by the "etched foil" technique. The R.A.E. disk is currently made by a photo-etching technique, with the eroded insulating sections filled by a good insulating material and the final surface given a ground finish.

The coded disk dimensions are determined by the desire for minimum size, weight, rotational torque, and inertia loading for convenience of application, on the one hand, and accuracy limitations in preparing the coded pattern and manufacturing the conducting and insulating surfaces, on the other. For a disk encoded into 1,000 parts over 300 deg. of shaft rotation, for instance, the length of one digit will be about 0·005 in. per inch radius. Most practical disks are, therefore, encoded with all the working switches grouped between radii of about 1·750 in. and 2·250 in., as this is the minimum size for reasonable accuracy of the final product with existing printed circuit techniques and the available precision in the mounting and assembly of the brushes. It is

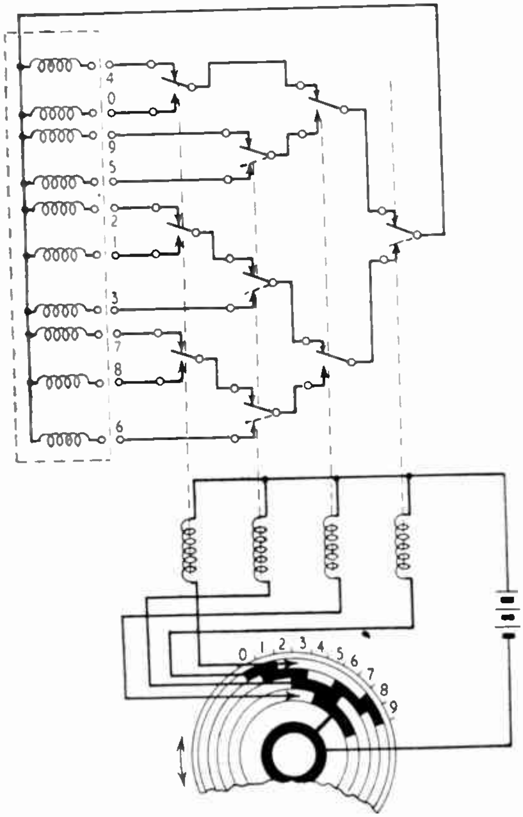


Fig. 5.—Translator from cyclic to progressive decimal binary code into decimal digits.

usual to give a rhodium flash or gold flash finish to the switch, consistent with the prevailing practice in contact design. The brushes are in some cases conventional phosphor-bronze or beryllium copper wipers; in other cases ball bearings are used. In either case, dependent on the type of load on the switch, it may be necessary to de-energize the switching circuits while the shaft is moving, in order to avoid damage to brushes or plates from sparks; also, highly inductive loads, such as relay coils, require spark suppressors.

With these precautions and careful manufacture, in spite of continuous contact, surprisingly high life figures are claimed from shaft encoders. Users of disks have found barely measurable falling off of performance after several months of continuous use at fairly high speeds.

The disadvantages of shaft loading by a mechanical switch, and the risks of failure through mechanical wear have led some workers to replace the mechanical switch by a photo-electrical one. The switching pattern in these is identical to the mechanical switches described above, but the alternative conducting and isolating sections are replaced by transparent and opaque sections respectively, and in the place of brushes there are pairs of light sources and photo-sensitive devices, such as photocells or photo-transistors. Provided that the difference of signal level on the photo-detector for "on" and "off" signals is well above the light and electrical noise, this could in principle provide as reliable a switch as a mechanical circuit interruption. However, the detector output must be amplified before it can effect useful switching; and the bulk and expense of light sources, detectors, light focusing and screening normally involved in this approach seem to outweigh the advantage offered by the lack of friction and wear.

A device of this type has been described by W. S. Elliott.[21]

4.1.3. Shaft counters

In a different approach to shaft position digitizing the digital information is obtained, not by the positioning information, but by means of counting intervals whilst the shaft is traversing from zero to the balance point. In this method the angle of revolution of the shaft is divided into n equal intervals, and each interval is made to give a pulse. The digital output is then obtained by counting the number of pulses.

The pulse may be produced in a variety of ways. Cam-operated switching of the micro-switch type operated from a suitable gear ratio has been attempted. However, the shaft loading, the accuracy obtainable from the gear step and switching differential, and the difficulty of discriminating between forward and backward direction of rotation, are usually too great.

There is only one known device of this type available, produced in the U.S. by the Clary Corporation. A more practical approach consists of assembling a number of magnetic poles which rotate with the shaft and their passage is counted on a fixed point, provided with a suitable winding. This method has the advantage that it is free from friction, and that the number of pulses round the shaft may be high enough to require only a comparatively small gear step between shaft movement and the counting device. It is possible to add a small magnetic device to sense direction of rotation, and thereby control the count in a forward or backward direction.

The American Austin Company is producing a device of this type using a drum with 500 engraved magnetic slots and an electronic multiplier giving an overall resolution of 1 part in 4,000. A similar model, produced by the Telecomputing Company of California, is claimed to handle 200,000 counts per second.

A more practical approach is counting by photo-electric means, which will be discussed in some detail. This method, described among others by Colley and McAuslan[20] consists of attaching a disk to the shaft on which segments of blacked-out and transparent strips alternate. At a fixed point, a light source is focused on to a photocell. The disk rotation interrupts the path of the light ray, so that each black segment produces a pulse in the photocell current. Digitizing consists of counting the interruption pulses. It may be seen that the method can only be accurate if each measurement starts from zero, or another fixed reference point. Further, if the shaft overshoots at all in the process of taking up the required position, provision must be made for "counting down" in order to get the right result. The counting device employed must be capable of responding to the highest possible transient speed of the shaft in order to ensure that no count is missed, and provision must be made to avoid "dither" due to input noise or servo-hunting, in order to avoid possible mis-count in either direction.

The application for which this work was developed is individual weighing of masses. The shaft is a pointer rotating element of a standard type mechanical weigher. The absence of any frictional load is of great value in this application. Due to the comparatively long time intervals between weighings, it is possible to cope with the bandwidth requirements imposed by the highest and lowest possible shaft speeds, though the need to avoid miscounts due to "dither" imposes some difficulties.

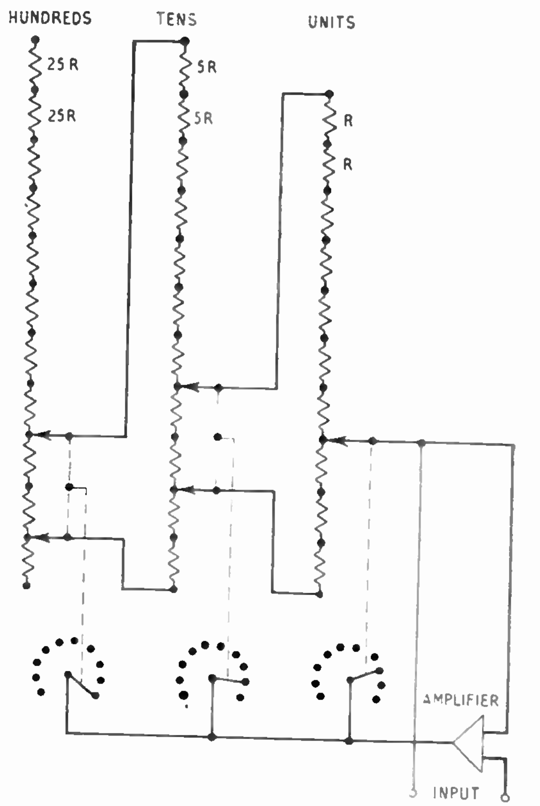


Fig. 6.—Kelvin-Varley potentiometer shown in "123" position.

In this work, the counting device consisted of simple Dekatron tubes with special provision to reverse the sequence of guide bars, and thereby direction of count, with shaft rotation direction reverses.

4.1.4. Sequential scanning digitizers

An entirely different approach to digital conversion of analogue voltage consists of dividing the voltage range into fixed increments, in which the smallest corresponds to the digital unit size. The digitizing consists of comparing the input voltage quantity with the fixed level successively until identity with the nearest available fixed point is found. The number of this particular position will be the digital equivalent of the input voltage.

The process of comparison is usually carried out by stepping switches which may be of the uniselector type. The total number of steps to achieve balance may be greatly reduced by scanning the range first in larger intervals corresponding to the most significant digit first, and stopping the process when—counting upwards—the digit reached exceeds the input voltage. A second ladder of resistance networks is then switched across this digit and is scanned step by step until balance is reached on the next significant digit, and so on. For a pure binary output, the range could be reduced by successive dividing by two, and a 1,024-part accuracy achieved by 10 comparisons. For a decimal output, each decimal digit involves 10 possible comparisons, so that a 3-digit accuracy may involve 30 steps—still a considerable reduction from the 999 possible steps in digit intervals.

One disadvantage of this system is that it can only deal with a single input law, usually the linear one. Any linearization of non-linear inputs must, therefore, take place before the digitizing stage.

The stepwise comparison in decimal stages is greatly eased by the use of the Kelvin-Varley type potentiometer networks, which offer constant impedance to the input (Fig. 6). By the use of bi-directional stepping switches, and a phase-sensitive discriminator amplifier, search for balance may replace the step-wise comparison process.

A stepwise comparator built on these lines (Fig. 7) has given satisfactory results on life tests carried out over more than a year. The speed of operation is in the main determined by the stepping speed of the switch used, and with components available here at the present time, it is doubtful whether a speed of one second per point can be reached. In American equipment of this type[22] 0·6 to 0·8 sec per reading is claimed. A simple laboratory-built version, prepared by British workers, is described by Dean and Nettell.[23]

4.2. *Electronic Analogue-to-Digital Converters*

The purely electronic techniques of analogue-to-digital converters have so far followed, in the main, three major and fundamentally different approaches:

(1) Voltage-time conversion and clock digitizing.

(2) Subtractive comparison method.

(3) Cathode-ray tube modulation method.

4.2.1. Voltage-time conversion digitizers

The basic principle of this method consists in converting the voltage to be digitized into time by comparing its amplitude with a precise fixed frequency saw-tooth generator, and measuring the time between the start of the saw-tooth and the coincidence with the input voltage. The time obtained is converted into digits by means of a clock pulse and a counter.

The general block diagram of such a system is shown in Fig. 8. The essential element of the time converter is the precision saw-tooth generator. Provided that the saw-tooth generator is perfectly linear and its slope

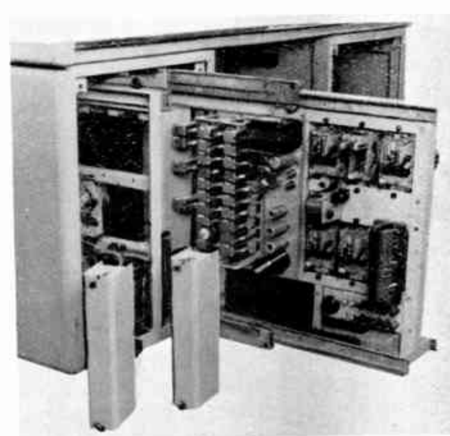


Fig. 7—(top) Uniselector digitizer (Elliott Bros. (London) Ltd.). The complete assembly with the typewriter.
(below). The left half of the equipment pulled out to show assembly details.

corresponds exactly to the digital calibration of the input voltage, the time interval between the beginning of the saw-tooth and the coincidence will be exactly proportional to the input voltage and the time measure obtained will be on the correct scale.

The saw-tooth generator may be any conventional oscilloscope time-base circuit, such as a Miller integrator, etc. The linearity of rise must, of course, be closer than the final accuracy of the digitizing required, i.e. for 1,000 parts it must be better than 0·1 per cent. Furthermore, this slope must be very accurately controlled, as any error in the slope will also give proportional digitizing errors. This latter point is usually achieved by means of a feedback amplifier adjusting the slope every time when the peak amplitude achieved differs from the standard reference voltage.[24]

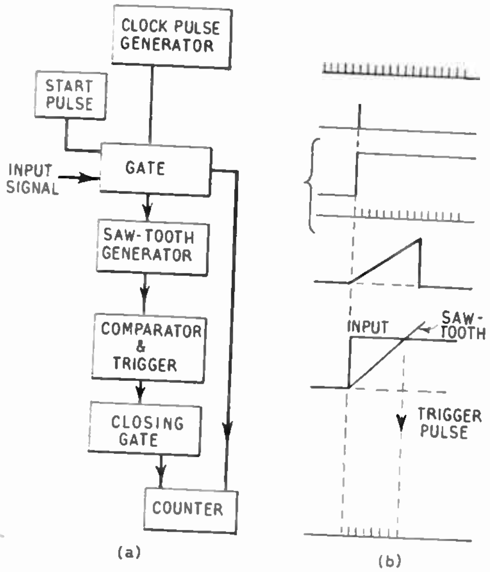


Fig. 8.—Voltage-time converter digitizer.
(a) Block diagram. (b) Corresponding waveforms.

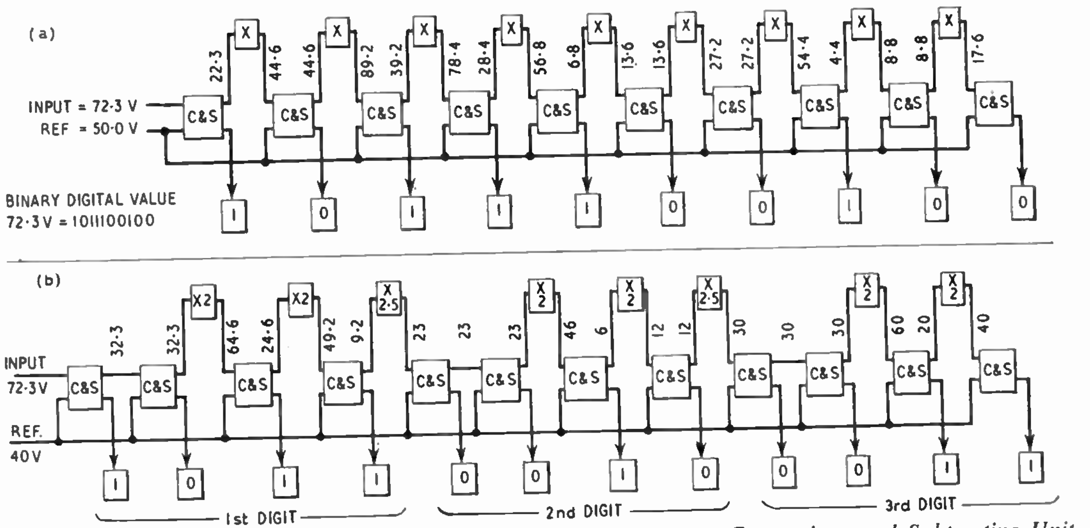
Considering now the whole of the block diagram, Fig. 8, it may be seen that the general sequence of digitizing is as follows:

A trigger pulse initiates the saw-tooth waveform, and at the same time opens the gate between the clock pulse generator and the counter. The counter, therefore, begins to count clock pulses and the rising saw-tooth waveform amplitude is continuously compared in the comparator and trigger. At the precise time when the input amplitude and the saw-tooth waveform become equal, the trigger operates and shuts the gate between the pulse generator and the counter. The total count accumulated in the counter will be the digital value that corresponds to the input voltage. In practical equipment the clock pulse may be of the order of 1 microsecond repetition frequency giving a count of 1,000 in 1 millisecond. This in turn implies a saw-tooth wave repetition frequency of somewhat longer than 1 millisecond. Taking into account the need for the counter to operate into some other store such as say a magnetic tape, and the necessary time lag for connection to the next input, the maximum rate of digitizing for an equipment of this sort is of the order of 500 readings per second. These figures are by no means limiting and claims have been made for much higher speeds of operation, using higher repetition rates of both block pulses and saw-tooth comparison waves.

Two limitations to the system will become immediately evident. First, the nature of the comparison technique and diode gate switching requires fairly large input voltages with full scales of the order of 50–100 volts. At this level, with 1,000 part discrimination, comparison and switching accuracies are of the order of 25–50 millivolts. However, with input levels of the order of 10–20 millivolts full scale, such as are obtainable for instance with thermocouples, switching accuracies would have to be of the order of microvolts which is not a practical proposition.

In consequence, when this system is employed it is necessary to amplify low level signals to the comparison level required for the saw-tooth technique. However, stable amplification of d.c. levels of the order of microvolts with an amplification factor of about 1,000–10,000 is, as is well known, a very difficult problem. The nearest thing to an adequate solution is offered here by the chopper amplifier which, however, introduces a new minimum time constant the equivalent of at least 1–2 cycles of the chopping frequency, which is, at best, very much longer than the sampling frequency available from the saw-tooth comparator digitizer.

Another disadvantage of the system is that for reliable operation the clock pulse frequency and the slope and amplitude of the saw-tooth wave must remain constant for all samples. In consequence, there is a single digitizing scale



C. & S. = Comparison and Subtracting Unit.
X = Multiplier Unit.

DIGIT	CODE
0	0000
1	0001
2	0010
3	0011
4	1000
5	1001
6	1010
7	1011
8	1100
9	1101

Fig. 9.—Subtractive comparison digitizer.

(*a*) *In pure binary code.*
(*b*) *In binary decimal code using 4, 4, 2, 1 comparison steps. The number of steps shown may be reduced by building in the rule to write, after a first zero, a second zero without testing, and after a one in the first two steps, write automatically a zero for the third step.*

available for all inputs measured. Where amplification of inputs is used, this drawback may be removed by using different amplification factors for each input. In some data-reduction systems all inputs are homogeneous and the disadvantage does not apply here either; but in the general case of direct reading of inputs the single scale available limits the usefulness of the arrangement. Similarly, there is no easy means of dealing with non-linear inputs.

There are some variations to this basic method. Instead of the saw-tooth comparison, the voltage to time conversion may be carried out by other pulse width modulation methods. Another approach published recently converts the input voltage into variable pulse-repetition frequency and uses a fixed time-interval for counting.[25]

4.2.2. Subtractive comparison method

The principle applied in this digitizing method is to compare the input voltage with fixed reference voltages representing digits of the final answer. After each comparison, if the input voltage is greater than the reference, the reference is deducted from the input voltage, and a "one" is marked for the appropriate digit. If the input is smaller than the reference, a zero is marked. A further comparison of the residue with the appropriate reference voltage yields the next lower relevant digit, and so on. The simplest application of this method is in a pure binary system.

A block diagram of the steps in a subtractive binary comparator is shown in Fig. 9a. The first reference voltage compared is equal to half the full-scale input voltage. The result of this comparison gives an answer to the first relevant binary digit: 1 if the input voltage is greater, zero if it is smaller. If the answer is 1, the reference voltage is simultaneously subtracted from the input voltage and the residue is passed on to the next stage. The next stage of comparison takes place with a voltage which is one half of the previous reference and gives again 1 or zero for the next relevant digit, and so on.

In an alternative application of this method the reference voltage is retained as constant during the whole operation, and the residue input voltage is multiplied by 2 in each stage.

Evidently, the same answer is obtained by this method, which is illustrated in the example of Fig. 9a.

A series of successive comparisons of the input voltage or its appropriate residue can give the digital final answer in pure binary notation. Ten steps of comparison provide an answer which is accurate to $2^{10} = 1024$ parts, i.e. better than 0·1 per cent.

The critical part of this system is the accuracy of the reference voltage, and of the subtractions. Each stage from the first onward must, of course, be stable and accurate to better than the smallest digit to be read, i.e. usually better than 0·1 per cent. In order to achieve this accuracy and stability, again it is necessary to operate with input voltages at levels at which the minimum parts are of the order of 10 millivolts or more, i.e. at inputs of greater than 10 V.

The subtractive comparison method has been put into operation by the use of digital computing techniques, on a "circulating pulse" basis. The successive comparison operations of this method are controlled by a clock pulse. A delay of one pulse length is inserted in series with the residue of the subtraction and fed back in synchronism with the next comparison operation. By this means the total digitizing may be carried out at the rate of one significant digit per clock pulse, i.e. using 1 M/cs clock pulse, and 10 binary digits, the digital answer may be completed in 10 microseconds giving a total of between 50,000–100,000 samples per second.

The "circulating pulse" method could of course be substituted by a "parallel" operation in which all the digits are simultaneously compared and the final binary decimal answer produced as a process of selection of wanted and unwanted channels in a chain. This would, however, involve as many subtracting and comparing amplifiers as there are digits, all of them maintained at a high degree of stability and accuracy. For this reason the "serial" method of subtraction is generally preferred.

The process described may be applied, of course, to a binary coded decimal system, except that the number of digital steps is increased to four steps per decimal digit, and that special provision must be made for the correct programming. In order to achieve the result in four steps, more than one subtracting reference or residue multiplying factor may be needed. For instance, the first step may decide whether the input is greater or less than 5, the second step whether the residue is greater or less than 3 and the last two steps may be subtracting one each from the residue. Alternatively, the same result may be obtained by steps of 4, 4, 2 and 1, and an example of this is shown in Fig. 9b. There is at least one analogue–digital converter commercially available in the United States operating on this principle, and claiming speeds of 50,000–100,000 samples per second.

4.2.3. Cathode-ray tube modulation digitizing

This system, experimentally devised and published[7] by the Bell System Laboratories as early as 1948, uses the deflection of a straight line trace on the cathode-ray tube as a measure of input voltages. Digitizing is carried out by a mask placed in front of the tube which has coded openings very much on the same principle as the coded disks described in Section 4.1. The mask is divided into an appropriate number of binary digits (for instance, for a three figure decimal binary notation 12 digits) and each nth part of the displacement of the line corresponds to a different combination of mask openings. The arrangement of the mask is on the progressive cyclic system described in connection with coded disks, so that errors are limited to one least significant digit.

Reading is carried out by photocells, one photocell corresponding to each digit. In each position of the line behind the mask a number of photocells will receive light and others will not. The "on" state of the photocell corresponds to figure 1 and the "off" state to the figure 0. The sampling rate of this method is only limited by the intensity of the beam and the response of the time-base, modulation circuits and photocells. Readings of the order of 10,000 per second or more are obviously quite practicable.

The principal difficulty in achieving the required accuracy and stability is in obtaining a beam focus which can produce a beam less than one-thousandth of the width of the total available beam traverse. Photocell inputs and sensitivities must be of a very high order, as must be the manufacture of the mask, in order to avoid errors and inaccuracies. This method of digitizing has been applied in some United States projects, but as far as it is known, it is not commercially available.

5. Other Data-Reduction Elements

5.1. *Input Devices and Transducers*

The complete range of input devices measuring industrial and similar process variables is very wide and there is literature available describing it. We limit, therefore, our description to devices which give direct electrical output, and transducers which convert measurements in other units into electrical quantities.

There are but few primary devices which produce electrical output directly from the measured quantity. The most important among them are temperature measuring devices, mainly thermocouples (giving thermal e.m.f. in a closed bi-metal circuit, when the two junctions are at different temperatures) and resistance thermometers (in which an electrical resistance element made from a material of high temperature coefficient is placed into the ambient temperature measured and connected in a bridge, with the other bridge elements maintained at constant temperature; the degree of unbalance giving the measure of temperature change).

Some measured parameters have electrical outputs in an obvious and conventional way; for instance, rev/min measured by tacho generators, light quantities measured by photocells, etc.

A large amount of process measurements relate, however, to pressures, flows, levels, strain, mass, etc., in which there is no easy direct means of obtaining electrical output. Conventional measuring instruments in these fields provide a small displacement as a measure of the quantity. In the measurement of flow and level there are some exceptions to this which will be described later.

The most usual way of measuring pressure is by means of a diaphragm or bellows. The displacement of the diaphragm against the retaining spring force is the measure of the pressure applied. Total displacement of the diaphragm for full-scale deflection usually does not exceed a few thousands of an inch. Bourdon tube devices operating on a similar principle give slightly greater displacements.

One of the most frequent ways of measuring flow rates is by measuring differential pressure along the flow line before and after the flow has passed a restriction point, the pressure drop being proportional to the square of the flow rate. Tank level is also often measured by means of diaphragms giving the pressure exercised by the column as a measure of liquid level.

For a large number of existing reliable primary devices it is necessary therefore to convert very small displacements into an electrical quantity. The two most important types of transducers to carry out this conversion are the differential transformers and the strain gauges.

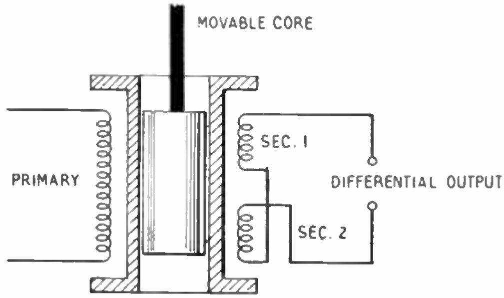


Fig. 10.—Differential transformer.

A differential transformer[26] consists of a winding assembly in which the primary is looking into an electrically and physically matched pair of secondaries. The coupling between the windings is obtained by a core which can be moved and which in its centre position gives identical coupling to the two secondaries (Fig. 10). With the core in its central position and the secondaries connected in opposition there is obviously zero output from the secondaries. If, however, the core is displaced in either direction the coupling factors of the secondaries change and one or other of the secondaries will have a higher voltage developed in it. The two secondaries do not cancel any more, and an unbalance output is obtained which is a measure of the core displacement.

Differential transformers are normally rated in terms of voltage unbalance per thousandths of an inch of core displacement, and per voltage energizing supply. It is possible to obtain figures of the order of 1 millivolt per volt input per 0·001 in. and linearity over an appreciable fraction of an inch. Care must be taken to exclude any extraneous couplings, or other noise signals at the excitation frequency in order to avoid residual quadrature voltage outputs at the nominal balance position of the core. The core may be made to have very small mass and friction so that it imposes a negligible load on the primary device which provides the displacement.

Strain gauges are the other important devices used to measure small displacements.[27] The picture of a strain gauge type transducer is shown in Fig. 11. Strain gauges measuring circuits are very similar to that described for resistance thermometers. The basis for measurement is the resistance change in the wire when it is put under strain or stress. In the type shown four wires are placed between the centre peg and the corners of the fixed frame.

Fig. 11.—Strain-gauge transducer.

The centre peg is subjected to displacement through the base of the instrument, and as a consequence the two upper wires contract and the two lower ones expand. If the four wires are so connected that the expanding ones and the restricted ones form the opposing arms of a bridge respectively, this bridge will be at balance with no displacement of the peg, but will give an unbalance reading when the peg is moved. The instrument shown provides an unbalance of approximately 1 millivolt per volt energizing per 0·001 in. displacement. The limit of linearity is at around 0·006–0·008 in. total displacement. The output obtainable for the few thousands of an inch displacement is, therefore, quite adequate to drive a self-balancing bridge when the strain gauges are energized from a source of the order of 10–12 V which corresponds to the maximum current-carrying capacity of the strain gauge wires.

In another application strain gauges are bonded to some elastic material which is made to support a mass or the stress of some working apparatus. These billets with strain gauges bonded on to them, usually called load cells, find increasing use in weighing and the measurement of stress such as cylinder pressures, or drawing dies, extrusion moulding etc.[28] The principle of measurement is the same as the unbonded strain gauge. The strain elastically deforms the billets, the total dimensional changes amounting to a few thousands of an inch. Through the bonding the stresses are transferred to the wire gauges which change their resistance in proportion to the stress applied. They are normally connected in a bridge circuit with some passive elements; the bridge unbalance is the measure of the weight or dynamic load.

Strain gauges and differential transformers are sometimes employed as "open loop" measurement elements, i.e. the unbalance voltage is taken directly as a measure of the primary quantity. However, there are increasing numbers of instruments which incorporate "closed loop" systems. In this approach the measured element causes an error signal: this actuates through a servo-amplifier a restoring force which brings back the displacement element to its original position, or as near its original position as the finite servo gain permits. The measure of the original quantity is then derived from the measure of the force required for restoring. The most convenient force is, of course, electromagnetic as this can be easily produced by standard servo amplification methods, though for convenience in some cases pneumatic or hydraulic restoring forces may be used, which are in turn controlled by electromagnetic valves.

The chief advantages of the closed loop system are that the non-linearities arising from the characteristics of the original displacements system, such as diaphragm, bellows or Bourdon tubes are eliminated and that the measurement is available at the output of a servo amplifier at comparatively high power levels. Also, this method may offer easy means of compensating against non-linear characteristics of the original input quality. Flow rates, for instance, when measured through differential pressure across an orifice, are proportional to the square root of the pressure differential. To calibrate against a square root law is ordinarily a fairly elaborate and difficult process. If instead a servo restoring force is supplied in a closed loop system, in which the magnetic pull varies with the square of the current, then the current delivered by the servo amplifier will be a linear measure of flow rate.

There are other flow rate measuring instruments which deliver their output in electrical terms. One method is to place a light propeller into the flow. The flow rate can be determined by measuring the propeller shaft speed which will be proportional to the flow. It is also possible to make the propeller vanes from a magnetic material and place coils round the pipe which can detect and count the passage of vanes. This method produces a digital answer for rates by counting during a fixed interval, and it can also provide a digital measure of total flow by the simple method of summating the total count of vanes during the integrating period.

Another electrical flow measuring device is applicable only to liquids which are at least slightly conductive. Here at a given point of the flow pipe a magnetic field is created, inducing a magneto-motive force in the liquid which behaves as if it were composed of a set of conducting filaments. Further along the tube the induced m.m.f., which is proportional to the flow rate, can be detected between the two pole pieces. The measurement imposes no restriction on the flow and, by use of a suitable a.c. magnetization, can be accurate and linear for a wide range of flow rates.

For level measurement apart from the mass measurement by means of diaphragms or load cells, mentioned above, a widely applied method is to use a float on a liquid surface, which will wind itself up and down with the variation of level. The measurement can be carried out on the winding shaft, either by gearing the wiper of a potentiometer to it, or by synchro type angular position transmitters, or coded disks of the type described in 4.1 which can supply an already digitized answer.

A further group of instruments converts small linear or angular displacements into electric quantities by the use of a mirror, and photocell detection of angular changes from a fixed light source.

There are a number of specialized measurements employing a diversity of electronic and electrical techniques which cannot be adequately surveyed here. Dimensional gauging is often done by capacitive methods. Viscosity may be measured as the rate of damping on an ultrasonic transducer of the magnetostrictive or barium titanate type. The oxygen contained in gases may be measured by the paramagnetic effect of oxygen in magnetic fields, etc.

5.2. *Programmers*

Programmers have two major functions in data-reduction systems. One of these is, basically common to all types of installations, the organization of the sequential scanning of input points. The other function, that of general instructions controlling the type of service provided, varies very greatly from system to system, and even in a family of systems employing the same techniques, may vary appreciably from installation to installation.

5.2.1. Scanning elements

The primary function of the scanning element is to connect in turn each input point to the digital equipment, and to supply the digitized answer to the record in the correct position. The simplest way to achieve this is in the form of a stepping switch such as the standard Post Office type uniselectors, which are available with 25–100 switching positions, and with 8–12 poles switched simultaneously. If the number of points exceeds the maximum capacity of one stepping switch, several of them may be connected in series, so that the last step of any switch automatically starts the following switch from the zero position. They are available with step-by-step actuators which can be controlled from a clock motor through a cam if the scanning is done according to a fixed time sequence, or they may operate from an external pulse, provided by the equipment, for instance, as a signal that the previous logging point has been completed.

According to the nature of the equipment, the scanning sequence may have to cater for a number of other instructions as well. In the case of tape, punch card, or strip record for instance, it is necessary to record the code numbers or letters of the input point, together with the reading value, and some poles of the stepping switch would be used to issue the necessary instructions to the logging equipment for this purpose. Similarly, any particular input point may require additional instructions with regard to its calibration, possible correction of a non-linear law, digital scaling, energizing of the primary device or of the transducer at the time of scanning, and in some types of records the possible insertion of decimal points and of additional zeroes or suppressed digits into the result. Unless any of these corrections are shared by all the points scanned, each point must carry its own specific instruction. With

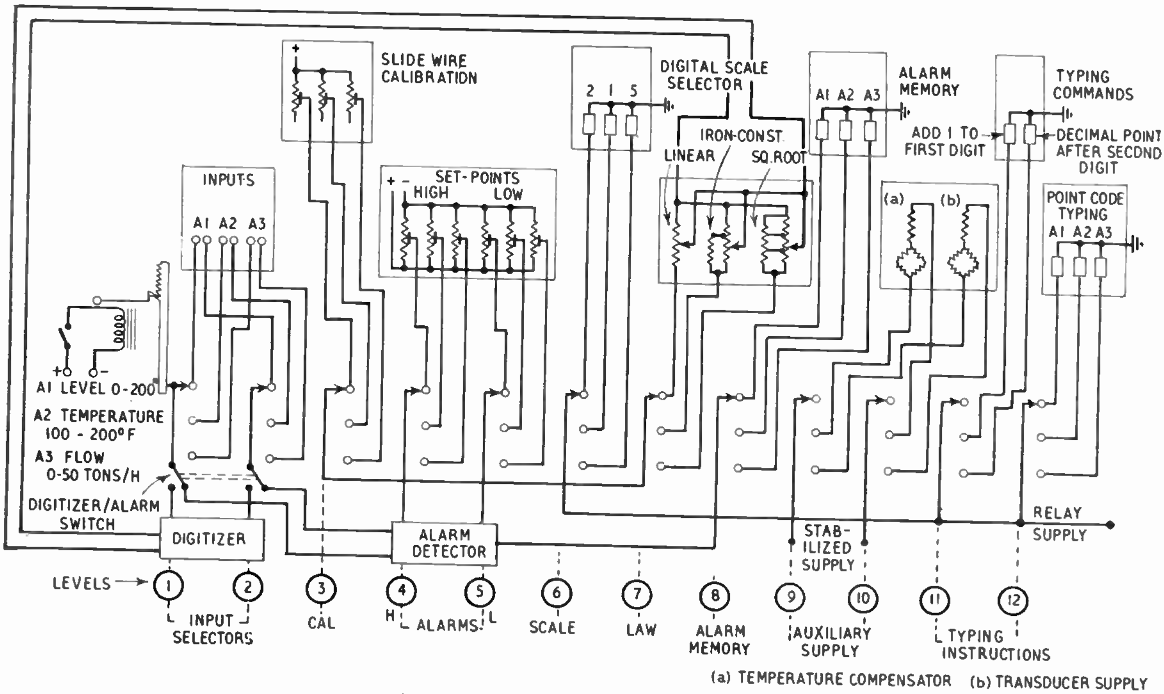


Fig. 12.—Scanning switch programmer.

a mixed system catering for a variety of different inputs, the number of instructions per point may well exceed the number of poles available on the stepping switch and slave relays may be needed to carry out the necessary instructions. Alternatively, a switch point may operate on more than one instruction though in this case it is necessary to use blocking diodes in order to prevent "cross-talk" of the instructions between the different points. A scanning switch section illustrating some typical programme instructions is shown in Fig. 12.

From the point of view of speed of operation, the available stepping switches such as uniselectors with speeds of operation of one to some tens of points per second are quite adequate. However, when it comes to high speed scanning, such as may be required for electronic digitizing of the type discussed in Section 4.2, no mechanical switch is equal to the task. The mercury jet switch which has made its appearance in the last two years offers speeds very much in excess of any electro-mechanical switch, but has other limitations, particularly in the fact that it can only cater for a restricted number of poles. Its speed, which may be of several hundred points per second, is nowhere near the capacity of 50,000 scans per second available on some electronic digitizers. The satisfactory answer to high speed input switching is still to be found.

In the electro-mechanical type of digitizing the stepping switch is a convenient answer, except when it comes to handling low level input signals. On these levels, and also at medium speeds it is extremely important to have the input free from contact noise, thermal e.m.f. induced in the contact materials and pick-up noise. Recently gold-plated uniselectors and stepping switches have made their appearance, and this refinement goes a long way towards curing the troubles arising from low level signals. For greater safety, however, it is advisable to use uniselectors only as sequence controllers operating on the coil of a slave relay, and use for the switching of the actual input lines high grade sealed relays with gold or platinum contacts.

The stepping switch type of scanning sequencer does not offer much flexibility in rearranging programme sequence. In many cases the logging programme may need to be

Operation Sequence

1. Logging cycle switch closes and through normally made contact of RF/1 energizes R1.
2. R1 operates; first input is digitized and logged; R1/1 is pulled in.
3. On completion of log "Record finished" switch closes and energizes RF; RF/1 momentarily changes over and, through second coil of R1, energizes first coil of R2.
4. R2/1 and R2/2 are pulled in.
5. R2 digitizing starts. RF is reopened, and in the change-over R1 falls out. R2 is held in through R2/2 and normally made contact of RF/1.

. . . Procedure is repeated until the *n*th relay. De-operation of last relay energizes "logging cycle finished" relay which breaks logging cycle switch. Chain is ready for the next cycle.

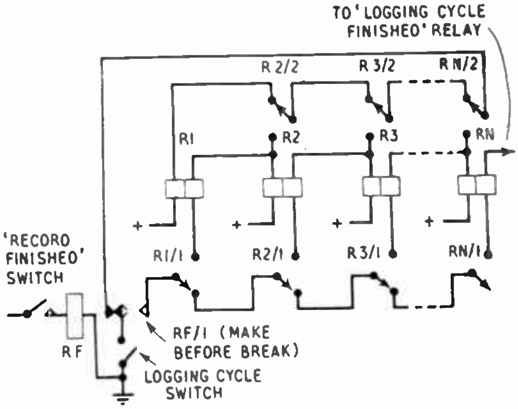


Fig. 13.—Relay chain.

varied from time to time due to changes in the plant or changes of emphasis in the records required. If, for instance, one measuring point incorporated in the sequence becomes redundant on the stepping switch programmer, there will be either a blank column left in the record, or a substantial part of the programmer must be completely rewired in order to advance all the positions by one step. In such cases the stepping switch may be replaced by a chain of interlocked relays providing their own sequencing. The diagram of such a chain is shown in Fig. 13. From the point of view of wear and maintenance the relay chain has the further advantage that each element is only operated once in a cycle instead of the continuous operation of the stepping switch mechanism, and also that in the case of a breakdown only one measuring point is put out of action instead of the whole sequence.

The other duty of the programmer is to initiate the sequences of the general data-reduction programme. The requirements of these vary, of course, from plant to plant. Generally speaking these commands are entrusted to relays which are closed either by a clock pulse (if the operations are to take place at pre-determined time sequence), or by manual switches (if the operations are "on demand") or they may be closed by some external switch operated by some event in the process such as the completion of a given operation. In some systems, apart from periodic automatic complete log records, there is a requirement for continuous or frequent scanning of all the input points and records are required when any of the points exceed certain set-points limits. In this case, the function of the programmer is to initiate or maintain the cycle of scanning and, when a deviation is recorded by the alarm scanning equipment, to bring the digitizing equipment back into operation in order to digitize and record the abnormal value. The programmer may be required to carry out some occasional tasks such as to record accurately once a day or once a shift the totals from the integrators, and to clear and re-set those integrators. The possible combinations of varying commands with superimposed priorities of certain commands to others are very large, but it may be seen that fairly simple circuits will always be capable of carrying out these commands.

5.3. *Deviation Detectors and Alarms*

In any process which in normal operation conforms to known and static parameters, the rapid and frequent recording of practically invariant data is of little value, and a record in which the revelant points are hidden among hundreds of irrelevant figures would make the task of interpretation unnecessarily complicated. It is, therefore, of interest to build into the data-reduction equipment elements into which the expected behaviour of a system may be pre-set. The record can then be limited to the time and points where the process deviates from the normal values. Since for digitizing purposes each input is converted into d.c. potential, the easiest way of achieving deviation data is to provide voltage dividers into which the upper and lower limits of the normal value may be manually set. The detecting equipment consists then of a simple comparator amplifier which accepts simultaneously the input voltage and the manually pre-set set-point voltage. If the input voltage exceeds the pre-set upper limit or falls below the lower limit, the deviation detector will close the appropriate self-locking relay.

Since the deviation detector carries out a single comparison check by purely electronic methods, the deviation scanning can take place at much faster rates than the digitizing and recording and is normally limited only by the permissible rate of input switching and relay operation times. Deviation scanning at the rate of 5 or 10 points per second can be achieved by the simplest means. If the set point level calibration is required in terms of the measured parameter at high accuracy, each set-point would have to be provided with either high accuracy precision potentiometers, or individual calibrated accurate scales. To circumvent this, it is possible to use the digital equipment as a calibrator for set-point setting. Operation of a manual switch will feed the set-point value in place of the signal of the appropriate point into the digitizer, and the digitized value of the set-point setting may be either produced on the record, or visually displayed. Since the switching sensitivity of the detector can usually be made much better than the lowest digit of the variable, by this method of setting there is a certainty that the deviation detector will operate at exactly the digit at which it has been set. The picture of such an arrangement is shown in Fig. 14, which is the set-point panel for a 50 point data-reduction unit. In the centre of the illustration is the visual display unit and selector switches. Each point has its associated high and low set-point potentiometer and helical potentiometer giving approximately 5,000 part discrimination. Knobs are provided with coarse calibration only to assist the operator in assessing the rate of turning. Accurate calibration takes place by operating the push-button for the appropriate point, together with the high or low push-button on the upper right-hand side of the centre panel. The circular visual displays show the digital value of the set-point setting selected, so that the correct setting is obtained by turning the knob slowly until the right figure appears in the windows.

When the deviation detector observes any abnormal reading it is usually required to produce a record of the time and the value of the point; the point itself will have to be identified either by recording its number or other identification code or else by placing the deviation record in the appropriate column of the whole log sheet.

In addition to recording the presence of an abnormal reading, other action may be required, such as audible or visual alarm, or actuating of on/off controllers, for instance to open or close a valve. The practice is to provide on the alarm detector a switch with at least two poles which may carry out any of the above functions according to requirements.

Alarm cancellation requirements may also vary. In some applications the alarm can remain operative until it is manually cancelled. In another case the alarm is automatically cancelled when the next scanning reaches that point and re-operated if the abnormal condition still persists. Finally, in some cases the alarms are provided with a self-locking relay or similar memory, and successive scanning cycles take no fresh action if the abnormal condition previously recorded still persists, but will make a fresh record on the first occasion when the condition is found to be returned to normal limits.

5.4. *Digital Recording Elements*

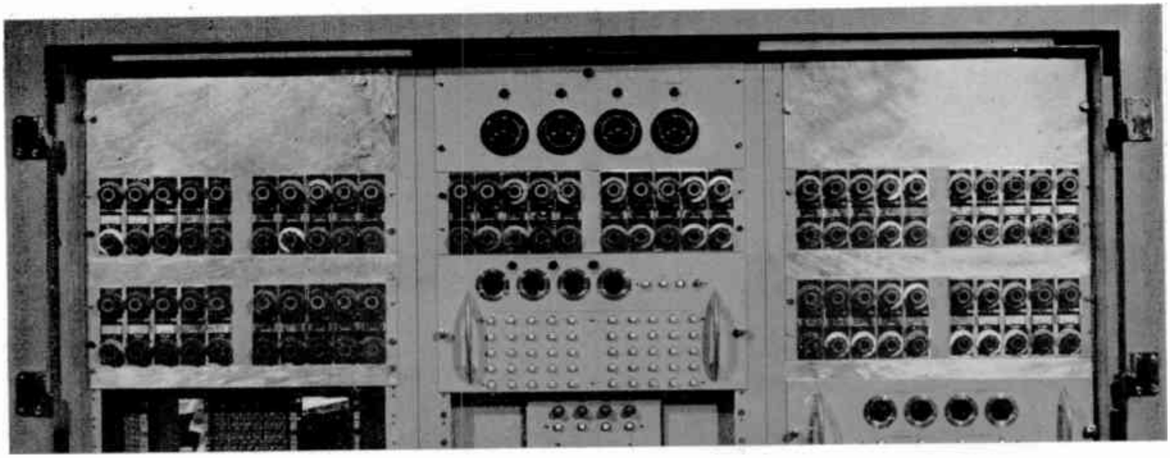
Digital records are produced in the main in three forms; automatic typewriters giving typed records and log sheets; punch cards or tapes, mainly for computing and accounting applications; and magnetic tape in the case of high speed records, and again mainly for computing work.

5.4.1. Automatic typewriters

The standard instrument available for producing automatic records is an electrical typewriter converted to remotely controlled operation. Four such machines are now currently available: Underwood, Olivetti, I.B.M. and Flexwriter.

The provision for remote control operation is made by fitting solenoids to each key (or at least to each key required for remote operation, which may not be the full keyboard), and to levers operating other commands such as space bar, tabulator, line change, carriage return, ribbon colour change, etc. The solenoids are either operated from a capacitor discharge, or from a direct d.c. supply pulse.

The remote commands to the typewriter are in the simple form of a pulse provided by the



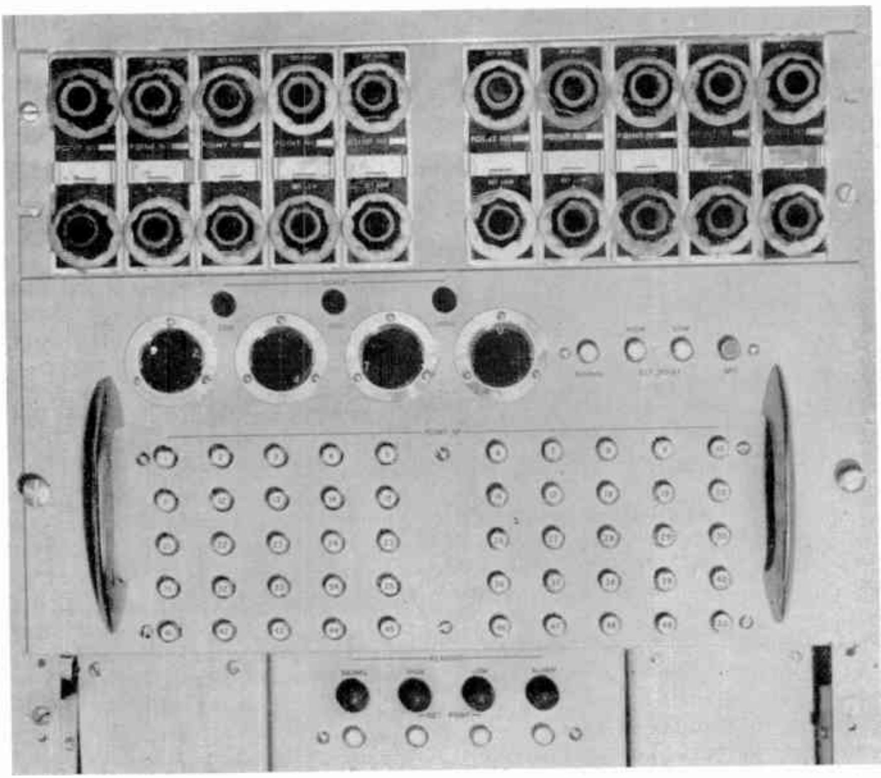


Fig. 14.—*(above)* 50 *point set-point and display panel. (below) Enlarged view of centre section to show display.*

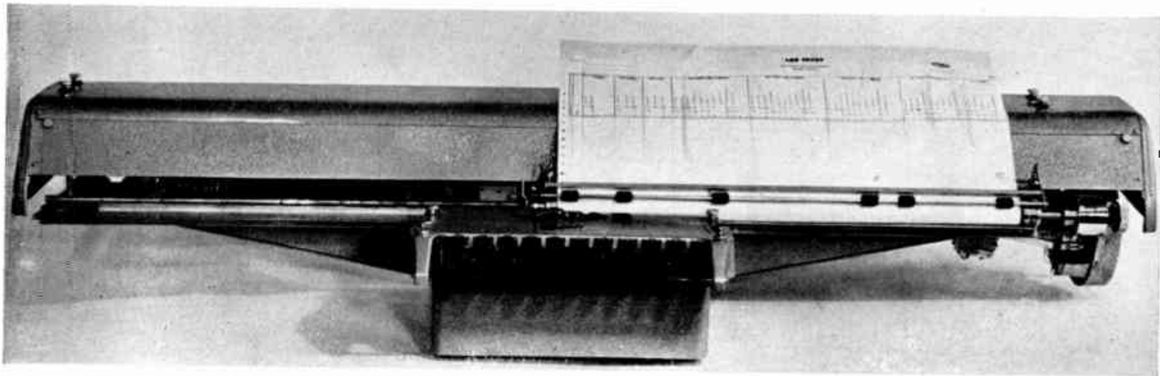


Fig. 15.—Automatic electric typewriter with log sheet (Saxby Compuprinter).

closing of relay contacts or switches in the digitizer or programmer. Through these switches the supply is applied to the solenoid and the typewriter is enabled to perform the required operation; the typing of a character, a space, or the carriage return and line change. The required pulses for solenoids are normally of approximately 50 milliseconds duration. Since the solenoid only operates on a lever and the final typing is by inertia, a delay is necessary in order to allow the previous key to fall back before the next one rises. Consequently, the maximum speed obtainable from automatic typewriters is of the order of 10–12 characters per second.

Automatic typewriters suffer from some shortcomings inherent in the history of their development. The original instrument is a mass-produced mechanical typewriter, and the electrical operation must be fitted on to this design. Consequently, the basic motion of the carriage is that of a spring release against a ratchet. The space available for solenoids is fairly cramped and therefore the operation is fairly critical; a minor fall in either amplitude or duration of the energizing pulse may result in failure to type a character or to move the carriage by one step. In some designs, increasing the time or the amplitude will result in double typing of the character, in others the power rating due to the limitation of space is such that any increase in input power will cause solenoid failures. The effect of these failures is aggravated by the fact that there is no feed-back information available from the typewriter to indicate that the command to type or to move one step has been effectively carried out. A figure or a space missed in one column will thus cause the rest of the whole line to be displaced by that amount. Also, when there is a requirement to place a record in a specified column of the sheet there are no direct means to drive the typewriter to the required space, and the column required must be found either by driving the typewriter step by step on the space bar, and counting the steps, or possibly by the use of the tabulator carrying out the same operation column by column.

These shortcomings appear to be overcome by developments carried out by R. N. Saxby in this country who based his design on the requirements for an automatic remotely controlled printer rather than the adaptation of the existing mechanical typewriter. There is no manual keyboard in the conventional sense; the keyboard is designed to operate from electromagnets and the electromagnets directly operate the printing means without a complicated sequence of leverages. The carriage motion is a positive Geneva wheel drive from a constant speed motor giving a fixed typing speed of 20 characters per second. The carriage in its progress also drives wipers over fixed contacts in four or eight banks, which may be used as feedback information to check that the typewriter has carried out the required operation, or to drive the carriage to the beginning of any particular column by means of telephone line seeking techniques. In some cases, the available contact arrangement may be used to carry out part of the normal programming task. With a maximum capacity of about 400 characters per line against the maximum of 300 of the modified conventional electric typewriters, this development appears to offer a much improved answer to automatic record production.

This typewriter, with a 24-in. logsheet inserted, is shown in Fig. 15.

5.4.2. Punch and magnetic tape devices

High-speed electronic type digitizing devices cannot operate directly into typewriters as the maximum obtainable speed of the latter would slow down excessively their rate of operation. Almost the only means available for permanent records at the rate of several hundred to some hundred-thousand decimal digits per second is magnetic tape.

At lower speeds of operation the information obtained may be required exclusively or alternatively for computer evaluation. According to the type of computer used, punch cards or punch tapes are chosen as the medium for information. Both for magnetic tape and for punch card and punch tape the information must be provided in binary form. For computer use, the preferred information is pure binary, but if typed or other records are required at the same time the binary coded decimal is often retained, as this gives a pure decimal record without difficulty, and the conversion from binary coded decimal to pure binary is a simple task for the digital computer. The devices used for preparing magnetic tape or punch tape and punch card records are well known from the digital computer input techniques, and need not be described here. As was seen in preceding paragraphs the information obtained from any of the digital converter devices, and other additional information such as point coding, can be made available in the form and at the rates required for tape recording devices.

5.5. *Ancillary Apparatus*

5.5.1. Computing devices

In many instances, the direct readings of process instruments give information which must be modified or further computed before it discloses the true state of the process. As an instance, most flow measurements are modified by pressure and temperature values prevalent at the time of the measurement and in order to establish true mass flow, the nominal flow values have to be corrected according to pressure and temperature charts available with the flow meter.

Again in many cases, the instantaneous values of flow rates are of little interest and the relevant information is the total integrated rate of flow over a period. Similarly, in heat exchangers of all types the relevant information is the total efficiency of the plant measured as a ratio of aggregate input to aggregate output. This performance efficiency may not, therefore, be immediately obvious, particularly in processes using a variety of inputs and providing a variety of outputs.

Similar minor computing requirements arise in a number of processes. Computing equipments providing corrected or calculated values from primary information are usually expensive and, in most cases, the necessary calculations are performed manually with a large expenditure of labour and an appreciable time lag between the process and the knowledge of its true state.

Data-reduction equipment as described in this paper is a major piece of capital equipment, which must be adequately justified either by labour saving generally or, much more often, by the up-graded and speeded up information obtained from the process, which results in better quality or quantity of the final product. Further it incorporates high speed automatic information-gathering elements and provides this information in easily usable digital form. It is often a minor step, therefore, to add to it further elements which can carry out some of the computations mentioned, and provide correctly computed process information, if not in real time, at sufficient speed and frequency to be of real use in controlling the process. The elements involved in this computing are generally well known from analogue and computing techniques, and will be only briefly mentioned.

Corrections such as temperature or pressure adjustment of flow levels are in effect multiplication of two functions where both of them may be non-linear. However, the flow information must be linearized for digital recording purposes, and non-linear pressure and temperature corrections thus follow a fixed law which may be built into an analogue multiplier either of the servo or of the electronic type. It is often possible also to obtain a linear approximation to the correction in the limited region which is most relevant for the process, and the accuracies obtainable are often sufficient.

Integrators of the servo, R-C or sampling type are well known and need not be discussed in detail. Where the flow varies sufficiently slowly to give a close approximation at the rate at which the information is scanned for data-reduction recording purposes, the sampling methods of integration provide an obvious means of arriving at total figures. Since true total flow rather than true flow rate is usually important, the pressure and temperature corrections may sometimes be introduced with advantage into the integrating processes rather than the rate recording.

On the digital side, sums and averages are often of more value than the individual readings. To obtain sums such as the instantaneous or integrated output of units operating independently in parallel, only a simple digital adding unit is required, together with an accumulator store. As the individual instantaneous output is recorded, it is a simple matter for the programmer to arrange to put the digital figure at the same time through the adding unit, into the accumulator store. From this store, the programmer can call out the accumulated total and record it in the appropriate log sheet column, clearing the store at the same time.

Where averaging is involved, it depends on the type of application whether a simpler approach is to obtain the average by means of an analogue summing amplifier, or by dividing the digital sum by the number of input data.

Generally speaking it may be said that with regard to further computing, no standard techniques have been introduced into the data-reduction field, as yet. The available elements are known but the application is in general individually suited to the particular problem.

5.5.2. Digital clocks

An ancillary equipment which is almost invariably needed in data-reduction equipment is the digital clock. There are several standard designs available, based on two types of clock measurement, and two types of display. The simplest and most frequently used clock element is the ordinary clock motor which is available as a standard article, giving one pulse every minute. Where closer intervals are needed such as half minutes or 10 seconds, these may be obtained by a suitable cam operated by the minute pulse motor. The alternative standard method is that of the crystal clock which can provide, of course, fixed rate pulses at high accuracy at any desired interval.

Having obtained pulses at regular intervals, it is necessary to integrate and display them. The simplest form is the electro-mechanical clock composed of stepping switches which move one step forward on the lowest digit for each pulse, and are electrically or mechanically geared to provide the necessary steps on the higher digits. The visual display of the clock position may be obtained either by coupling a pointer to the stepping switch shafts, or by displaying electrically their instantaneous position by means of pilot lights or neon lamps.

The alternative method of integrating and displaying is the use of Dekatron counting tubes, which will progress one step with every clock pulse. They must be connected in such a manner as to transfer to the next digit at the correct position, for instance, after the figure 5 in the "tens" digit of minutes.

In either form of presentation the digital value of present time is readily available for typewriter or punch record any time the record is taken.

5.5.3. Trend recorders

In some processes or test installations subject to major short term disturbances, it is sometimes desirable to have a continuous record of the general trend of these disturbances. Standard pen recorders are available which can display 6, 12 or 54 variables simultaneously on a single 10-in. wide chart, which may move at speeds between an inch per second and an inch per day. Such trend records are often used as auxiliary to the digital log record. Connection may be arranged in the form of a telephone switchboard type patch-panel, so that the individual traces may be connected to any point manually when desirable. In other instances, the points where traces should be observed are fixed and permanently connected to the individual pens, and the data-reduction equipment automatically provides the start of the trend record every time when it observes a disturbance in the form of readings exceeding set-point levels. In a similar way, one or several indicators may accompany data-reduction equipment with a patch-panel switchboard arrangement which permits any point to be connected to the indicator.

This may be used for visual inspection of the behaviour of a variable and can be arranged so that the digital scanning overrides for a few seconds the instrument display. At the same time it can be used as stand-by instrumentation in cases of maintenance trouble on any point of the data-reduction equipment.

6. Conclusions

This short review of the existing systems and elements used in data-reduction equipment gives a broad outline of the present state of the art. It may be useful perhaps to outline in a few closing words the trends for the immediate future, as far as they can be ascertained.

It is clear that in its present development, data-reduction and digital techniques cannot live up to the somewhat wild "Automation" claims made for them on occasions. It is certain that digital methods of data processing and the techniques of reducing records by the elimination of irrelevant data have come to stay and there is no doubt that the next few years will see the introduction of them into many plants and many industries, at any rate in countries of advanced technology and in plants of medium and large size. In this period the direct application of automatically collected data to control is likely to be rather the exception than the rule excepting in the case of processes or parts of processes particularly suited for it.

Nevertheless, it may be forecast with certainty that the longer term of development will inevitably tend towards perfection of techniques which permit ever more comprehensive control of processes through digital programming. In this trend of development the new techniques in information gathering will play an important part, as programming for automatic processing implies an accurate and rapid knowledge of plant behaviour, which is not in general obtainable with conventional techniques. Consequently, on the application side it is possible to forecast that the immediate future will see a broader basis of data-reduction techniques established in many plants and in a variety of industries, together with a considerable use of trial-and-error approaches designed to assist in collecting the data and experience necessary for standardizing the techniques, programmes, etc.

On the technical development side, both in components employed and in techniques there are a number of items which cannot be considered as being solved even provisionally. Each one of them is absorbing a large amount of development and research effort, and one may reasonably anticipate that these will bring forward improved elements.

The major points on which effort is being concentrated are as follows:

(1) High-speed digitizers capable of operating reliably at low signal levels.

(2) High-speed multiple switches for the scanning of inputs.

(3) Improved transducers to measure process variables with higher accuracy and giving outputs more suitable for data processing.

(4) Improved computing elements to carry out simple computations at high speed and with high accuracy, particularly in the case of non-linear functions.

(5) Improvement in the field of high speed digital recording; automatic typewriters, strip printers, type punches, etc.

It may be seen that the immediate programme in the field aims largely at increased speed and reliability. These are primary requirements. At the same time, there are increasing signs that the up-grading of information accuracy brought forward by these new techniques will in turn create a new demand for even closer accuracies. An accuracy of 0·1 per cent. is now available for many measurements in which, up till recently, accuracies of better than 1 per cent. were the best obtainable. Already, however, there are occasions when the requirement for 0·01 per cent. is being formulated. Research effort is devoted in many laboratories to this further upgrading of measurements, but in some instances at least the problem seems to come up against irreducible levels of available information energy, signal-noise ratios, and other at first sight insuperable difficulties. The general aspect of development may be broadly and somewhat inaccurately summed up as a slow process of replacing components and techniques of mechanical, electro-mechanical and pneumatic nature by electronic and allied components and techniques. Here, however, as well as on the application side, it is safe to say that the replacement process will be slow and gradual and it is unlikely that within the next generation we shall see the complete disappearance of conventional instrumentation, even though alongside there may grow up an increasing number of devices based on the new techniques.

7. Acknowledgments

The information and experience leading to the present survey has been accumulated by a team working on data-reduction techniques with Panellit (England) Ltd. and Elliott Bros. (London) Ltd. Every member of the team has had his share in bringing together some part of the material so that we can only acknowledge them collectively. Special acknowledgments are due to Mr. A. F. Sperry and his team of Panellit Inc., Skokie, Ill., U.S.A., for much information on American field experience and equipment, and to Mr. C. A. Laws and Mr. D. W. Hobbs for the many valuable suggestions and criticisms.

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MEMBERS OF THE COUNCIL

Air Vice-Marshal **Colin Peter Brown,** who was born in 1898, was educated at Dulwich College. He served during the first World War as a fighter pilot in the R.N.A.S., transferring to the R.A.F. on its formation. He was awarded the D.F.C. and bar and the Croix de Guerre.

After the war he was for several years concerned with experimental flying duties, and in 1924 he qualified in the R.A.F. Long Signals Course. The next fifteen years were devoted to alternate periods on the Air Ministry Staff and with flying commands, and at the beginning of the second World War he was appointed Senior Air Staff Officer of No. 60 Group. This Group was responsible for all aspects of radar in the Air Force, and in 1942 Air Vice-Marshal Brown was appointed a C.B.E. for his work. From 1942 until the end of the war he held the important post of Director of Radar, and was appointed a C.B. in 1944.

From 1946 to 1948, Air Vice-Marshal Brown was Director of Operational Requirements at the Air Ministry, and for the next two years he was with the Middle East Air Force as Chief Signals Officer. On his return to this country, he was for three years Assistant Controller of Supplies (Air) at the Ministry of Supply, and from 1953 to 1954 he served at the Air Ministry on special advisory duties. Since his retirement from the active list, Air Vice-Marshal Brown has been associated with the Electronic Control Division of Redifon Ltd.

Air Vice-Marshal Brown was elected a full Member of the Institution in 1954, and in 1955 was appointed to the Membership Committee. He has served on the Council since October 1955.

Hugh Brennan was born in 1900, and received his general education in Newcastle-upon-Tyne and at Armstrong College (now King's College) of the University of Durham. After graduating with a B.Sc. degree in 1921, he joined the North Eastern Electric Supply Co. Ltd.

In 1930 he started his own business as a consulting radio and electrical engineer, being responsible among other work for the installation of sound cinematograph equipment. During the late 1930s Mr. Brennan became interested in wire broadcasting, and has established operating networks in various parts of North East England. Before the establishment of local television transmissions, Mr. Brennan also set up experimental wired television systems.

Elected an Associate Member of the Institution in 1938, Mr. Brennan was transferred to Full Membership in 1944. He was the joint author with Mr. A. Cross (*Member*) of a paper on Public Address Systems, published in the *Journal* in 1943. Mr. Brennan was the first Chairman of the North Eastern Section on its formation in 1943, and has since served the Committee in other capacities. He has recently again been elected Chairman.

David Latcham Leete was born in London in 1918, and was educated at King's School, Ely, and at King's College, University of London, where he gained his B.Sc. degree in 1941.

From 1941 until 1945, Mr. Leete was engaged in work on airborne radio countermeasures at the Royal Aircraft Establishment, Farnborough, and subsequently at the Telecommunications Research Establishment at Malvern (now the Radar Research Establishment). At the end of the war he transferred to the Ground Radar Department to work on transmitter research and design problems.

Mr. Leete was elected an Associate of the Institution in 1941, and was transferred to Associate Membership in 1943. He took a leading part in the foundation of the new South Midlands Section based on Cheltenham and Malvern, and has been elected its first Chairman.

INDUSTRY'S CONTRIBUTION TO FURTHER EDUCATION

A recent publication by the Federation of British Industries* emphasizes the need for closer co-operation between industry and the technical colleges if colleges are to provide the right type of technical training required by industry. The present time, when so much attention is being paid to technological training, offers an excellent opportunity for the study of existing and potential problems, and for a review of the links, both formal and informal, which exist between industry and the technical colleges.

One link is provided by industrial representation on the governing bodies of technical colleges; in itself, however, this is not enough. Many governing bodies have only *advisory* functions, with little control over major policy, so that industry's views and requirements do not always carry as much weight as they should. Where this applies, a revision of the composition and functions of the governing bodies would do much to attract the membership and active help of industrialists.

Liaison between industry and college departments ensures that college courses are in line with current industrial practices and needs, giving members of industry a good opportunity of exercising influence in the compilation of curricula, and keeping them in touch with the college staff. Representatives of industry and the colleges also serve on the Regional Advisory Councils for Further Education; each Council has a number of advisory committees dealing with technical and commercial education for the industries to be found in the region.

The complexity and variety of industry make the planning of technical education on a national or regional basis exceedingly difficult. Firms frequently require individually planned courses, and it is in connection with such problems that informal contacts are invaluable. A plea is made in the booklet for more personal contacts between technical college staffs and members of industry.

It is also stressed that the need is for an extension of the co-operation that already exists, rather than for a new approach. Increased opportunities for members of industry to become part-time teachers in colleges, more vacation work in industry for college staff and students, more works visits, and the extension of prize schemes for students doing part-time study, would greatly benefit both sides. The encouragement of teachers to carry out research and consultancy work, and their seconding to industry for periods of up to a year, would enable them to keep professionally up-to-date.

An important aspect of this co-operation may be described as flexibility. The college must be willing and able to adjust its courses and teaching methods to the changing requirements of industry, and the firm must plan its education and training programme with due regard to the facilities available at the technical colleges, and to their sources of recruitment, the secondary schools. It is also recommended that increasing use should be made of part-time day release and sandwich courses, and that the works training of students should, as far as possible, supplement the work done at the colleges, and vice versa. It is suggested that smaller firms should, where necessary, co-operate in jointly sponsoring specialized courses.

The provision by technical colleges of advanced short courses in applied science and technology is another factor which will enable those established in industry to keep abreast of current developments.†

The White Paper on Technical Education expects that Colleges of Advanced Technology should ". . . develop a substantial amount of research," and it is felt that this should, for the most part, be linked with the work of firms. Wherever possible, industry-sponsored research should be published; publication is both a natural right and an exacting discipline for staff and student alike, while the sponsoring firm will benefit from prior access to the results.

The efficient performance of such research work depends greatly on the equipment available, and firms can offer considerable assistance by donating equipment, or by the endowment of laboratories and workshops. In cases where a local college has no need of an item offered, a college in another area might be glad of it, and the establishment of regional clearing houses for this information would be helpful.

* "Industry and the Technical Colleges." Federation of British Industries, 21 Tothill Street, London, S.W.1, September 1956. 3s.

† A list of advanced short courses available in Great Britain in early 1957 is given on page (xvi) of this issue of the *Journal*.

HIGH FIDELITY LOUDSPEAKERS: THE PERFORMANCE OF MOVING COIL AND ELECTROSTATIC TRANSDUCERS*

by

H. J. Leak (*Member*) †

Read before the Institution in London on 30th November, 1955. In the Chair: The President.

SUMMARY

The significance of objective tests is dealt with in relation to the various properties of the loudspeaker. The characteristics of a hypothetically perfect vibrating disc are stated and the extent of their achievement in moving-coil loudspeakers for low and high frequencies discussed. In the ribbon loudspeaker the advantage of a uniform mechanical drive over the entire radiating surface is offset by the disadvantage of a small diaphragm area; this may be overcome by the adoption of electrostatic principles. The electrostatic loudspeaker is described and the considerable advantages of the balanced push-pull type over the single-sided type are pointed out.

1. Introduction

This paper is primarily concerned with loudspeakers for use in the home, that is, with loudspeakers which are not prohibitive as regards size, appearance, unreliability, or cost, and which are sufficiently sensitive to work with amplifiers of the usual domestic type having undistorted power outputs of the order of 10 watts. Under these conditions the term "high fidelity" is applied here to loudspeakers which reproduce speech and music as naturally, or almost as naturally, as is possible at the present time.

When one speaks of a loudspeaker having a certain degree of naturalness of reproduction one is assessing the subjective impressions derived from listening to it, and herein lies the difficulty of defining "high fidelity," for it is not often that any two people will agree entirely on the degree of naturalness or be capable of describing it in words. It follows, therefore, that some of the assessments made in this paper are personal, subjective impressions, and these impressions may not meet with universal agreement. These difficulties of agreement arise because all loudspeakers have known imperfections or distortions, and because the psychological attributes of hearing vary greatly between individuals. The tolerance or acceptance of distortions varies with individuals as regards the types, amounts and admixtures of the distortions.

2. Objective Loudspeaker Tests

It is possible to stipulate a series of objective tests on all the links in a sound reproducing chain, with the single exception of loudspeakers, from which measurements can be correlated (by experienced interpreters) with the results of listening tests. This is not yet possible to the same degree in the case of loudspeakers, and we are forced to rely greatly on listening impressions. This position is unsatisfactory and frustrating to engineers working on loudspeaker development, but it has to be faced. However, there is agreement that certain measurements can be correlated to some degree with the results observed when listening, and the general opinion is that four objective tests can yield information which is useful when interpreted with care and experience.

2.1. *Steady-state Frequency Response*

A characteristic commonly used to describe the performance of a loudspeaker is the steady-state frequency response, and this is often the only characteristic of any significance quoted in present-day specifications. There is a considerable body of informed opinion which agrees that the steady-state frequency response characteristic is of little value in assessing the performance of a loudspeaker when it is the only measurement given.

* Manuscript received 12th July, 1956. (Paper No. 378.)

† H. J. Leak and Company Limited, Acton, London, W.3.

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2.2. *Transient Response*

There is a growing opinion that study of the transient properties of a loudspeaker will more accurately predict its goodness as a reproducer than the steady-state frequency response. When assessing the transient response of a loudspeaker the accuracy of reproduction of square waves can be observed, and it is also enlightening to measure the rate of decay of sound after the sudden cessation of electrical signals applied to the loudspeaker. A plot is then made of the attenuation of the signal with time, and this graph is called "the delayed frequency response." It is found that a loudspeaker whose delayed frequency response is flat (and considerably attenuated below the steady-state level) will have a steady-state frequency response which is also flat. On the other hand, the steady-state frequency response of a loudspeaker may be flat, or nearly flat, and yet the delayed response may be peaky, pointing to the storage of energy which is apparent in the "hangover" of sound.

2.3. *Distortion Characteristics*

The next measurement on a loudspeaker which can yield significant information on its goodness as a reproducer is the distortion characteristic, which is a plot of non-linear distortion for a given electrical input signal. The distortion can be a measurement of total r.m.s. harmonic content from sine wave input, or it can be measured as the intermodulation products arising from the application of two tones, each of sine wave form. It is necessary to measure the sub-harmonic products as well as the harmonic products when applying sine waves. Many engineers believe that the results of intermodulation measurements are more indicative of the goodness of a loudspeaker than the results of harmonic distortion measurements, but there is not agreement on the methods to be employed when measuring and interpreting intermodulation distortion.

2.4. *Directional Characteristics*

The fourth physical test which might be expected to yield information of value in determining the quality of speech and music given by a loudspeaker is the directional characteristic. This is a plot on polar co-ordinates of the sound pressure level as a function of angle from the principal axis of the loudspeaker. If measurements are made at a number of frequencies the plots so obtained can be combined into a single plot to give a "directivity index" as a function of frequency. Now, it is difficult to assess the importance, precisely, of the directional characteristic. When walking across a room in which there is a loudspeaker operating it is often noticeable that one walks into a beam where the high frequencies are accentuated, and this is disturbing. If one sits in a selected position one's subjective impressions will be affected by the ratio of direct sound to indirect sound (reflected from the walls of the listening room) and this ratio will, of course, be influenced by the directional properties of the loudspeaker.

Clearly, if a loudspeaker in an infinite baffle has a "flat" pressure/frequency response when measured on the principal axis, but discriminates against the higher frequencies off the axis, then the total power radiated at the higher frequencies will be less than at the lowest frequencies, for which sound is radiated hemispherically. The importance of the directional characteristic as it affects the reproduction of speech and music has so far received little attention.

2.5. *Other Measurements*

There are three other characteristics to be kept in mind when designing loudspeakers. The *efficiency characteristic* is the ratio of the acoustic power output to the electrical power input. The *impedance characteristic* is a plot of the electrical impedance on a frequency base. The *rated power handling capacity* is usually defined in terms of the maximum electrical power which can be supplied to the loudspeaker without mechanical failure, though the author's view is that it would be better defined in relation to distortion rather than to breakdown. For instance, the author can cite a 12-in. loudspeaker rated at "20 watts power handling capacity" which has severe intermodulation distortion when supplied with one watt of audio power composed of a 1,000-c/s signal plus a 50-c/s signal, the latter being 6 db below the former. These three characteristics are related to the amount of electrical power which can be supplied by the amplifier, or to reliability, and they need no further attention here because they are covered by the opening assertion that the loudspeakers presently discussed will work satisfactorily in the largest room likely to be found in a home, with amplifiers of power ratings such as are normally used.

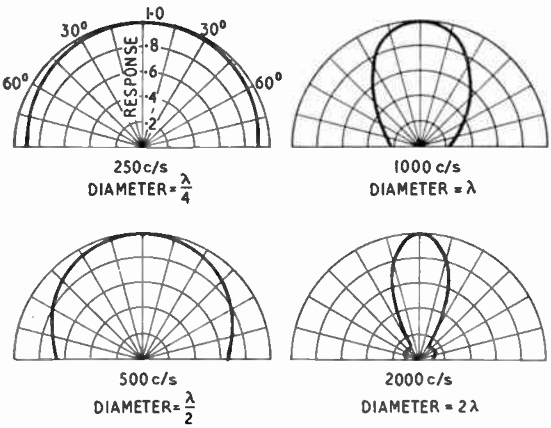


Fig. 1.—Directional characteristics of a circular piston source as a function of the diameter and wavelength (After Olson[6]*). Real frequency values shown for a 12-in. diameter circular piston or plate.*

p_α = *ratio of the pressure for an angle* α *to the pressure for an angle* $\alpha = 0$

$$p_\alpha = \frac{2\,J_1[(2\pi R/\lambda)\sin\alpha]}{(2\pi R/\lambda)\sin\alpha}$$

where

J_1 = *Bessel function of the first order*
R = *radius of the circle, in centimetres*
α = *angle between the axis of the circle and the line joining the point of observation and the centre of the circle*
λ = *wavelength, in centimetres.*

3. Hypothetical Circular Vibrating Plate

Before the characteristics of practical moving-coil cone loudspeakers are discussed it is of interest to consider the characteristics of a circular plate which is free to vibrate in an infinite baffle. Hypothetically, let us stipulate that the plate is mass-less, and that all parts of the plate vibrate with uniform amplitude and in phase (which is another way of saying that the plate is effectively infinitely stiff). If the plate is freely suspended in an infinite baffle it will radiate equally from both sides, but our interest is in the sound coming from the side facing us and the measuring microphone. If in some manner the output from an amplifier is converted into a mechanical driving force applied to such a plate, the plate will reproduce transients perfectly, and it will not generate harmonic, sub-harmonic or intermodulation distortions, because the plate is infinitely stiff and has no mass. The pressure/frequency response will be level when measured on the axis, but the directional characteristics of such a circular plate show discrimination against the higher frequencies when the measuring microphone is moved away from the central axis. The relationship between the dimensions of a circular plate and its directional characteristics is given in Fig. 1, this relationship being shown as the ratio of diameter to wavelength. Because we shall soon be discussing practical loudspeakers with cone diameters of 12-in., real frequency values have been appended for this particular dimension. The formula from which the directional characteristic is computed is derived from the fundamental laws of acoustic propagation. A circular plate tends to radiate sound hemispherically at the lower frequencies, but in the form of lobes at higher frequencies, and it can be shown experimentally that a practical cone loudspeaker will have approximately the same directional characteristics.

The vibrating plate focuses at high frequencies because of its shape—because it is flat. If we could mould its area into a pulsating hemisphere, mounted with its dome towards the measuring microphone, it would have a broader directional characteristic. The future may well produce electrostatic loudspeakers tending towards this shape.

4. Moving-coil Loudspeakers

In this investigation of practical high-fidelity loudspeakers, it will be found logical to start by assuming that high-fidelity bass reproduction is desired. At present (December 1955) the only way of reproducing bass from loudspeakers of acceptable domestic size, reliability and cost is by using the moving-coil principle, and this discussion is limited to direct-radiator moving-coil loudspeakers, that is, loudspeakers which are mounted in cabinets or baffles and do not employ horns. If good bass reproduction down to the lowest frequencies is required, then a diaphragm of reasonable area is desirable because with a smaller diaphragm the amplitude of motion to produce the same sound pressure will have to be greater, and this increased amplitude tends to introduce distortions due to non-linear suspensions and to varying flux linkage in the coil. For these reasons there is a widely held opinion that a

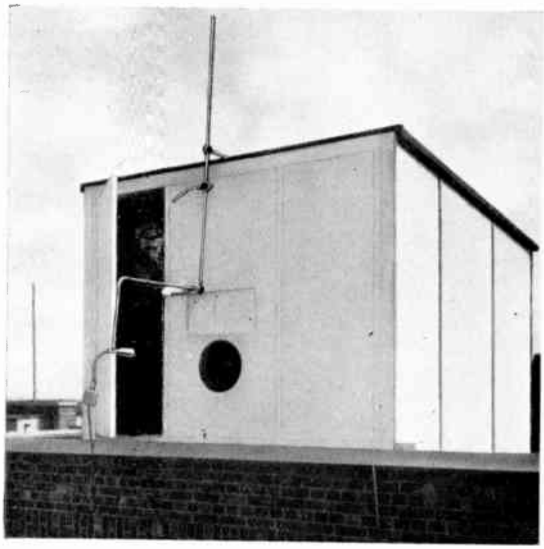


Fig. 2.—Reflection-free measuring station.

15-in. loudspeaker is the optimum size for reproducing bass in the home. Now, the diaphragm diameters of so-called 15-in. loudspeakers approximate to 12 in., and this is why, when previously considering the circular plate, directivity values were given for a diameter of 12 in. Because we are now going to consider the pressure/frequency response of practical loudspeakers, it should be emphasized that the environment of the roof-top measuring-station (see Fig. 2) is reasonably non-reflective and as good as an anechoic chamber ("dead-room") above 200 c/s, and better than a "dead-room" of practical dimensions below 200 c/s. This measuring-station is also effectively an infinite baffle.

Figure 3 shows the cone configurations of two 15-in. loudspeakers of different design, and though these differ it will be seen that there are marked similarities in the response curves. The similarities consist of: (1) a falling off below 60 c/s; (2) a relatively level response between 60 c/s–1,000 c/s; (3) a dip slightly above 1,000 c/s; (4) a rise to 3,400 c/s and (5) a falling-off above 3,400 c/s. It will be shown that these similarities are not remarkable: on the contrary, the general shape of the response curves may be predicted with surprising accuracy without recourse to a measuring microphone! Both loudspeakers are of conventional design; both have cloth surrounds; both have 2-in. speech-coils ("A" wound on a dural former, "B" on a paper former). Both have "hard" or stiff cones of approximately the same weight, and as the suspension compliances are of the same order, the low-frequency resonances will coincide (at 40 c/s approximately). Now, it will be observed that the curves show no sign of increased pressure response at 40 c/s, and this is because the bass resonance is more than critically damped by the internal impedance of the driving amplifier. We are discussing high-fidelity loudspeakers for use in the home, and these response curves were taken, logically, with a high-fidelity home amplifier. All modern low-distortion feedback amplifiers have output impedances which are one-tenth, or less, of the impedance of the loudspeaker at low frequencies, and it will be shown that the amplifier's internal impedance is the only parameter of any significance determining the magnitude of the bass response in the region near resonance.

4.1. *Electrical "Analogue" of Moving-coil Loudspeaker*

In all serious investigations into the behaviour of loudspeakers, recourse must be made to electrical analogues, whereby the mechanical and acoustical elements of a loudspeaker are converted into electrical elements, the resulting circuit then being amenable to analysis.[1] Now, it is impossible to draw a *completely* accurate electrical analogue because a moving-coil loudspeaker has several degrees of freedom. At best an analogue will only be a simplification, but

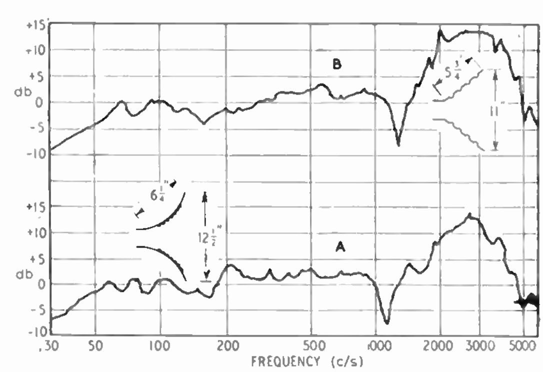


Fig. 3.—Axial pressure response of two 15-in. loudspeakers.

e_g = *open circuit voltage of audio amplifier (volts)*

R_g = *amplifier resistance (ohms)*

R_E = *speech-coil resistance (ohms)*

L = *inductance of speech-coil measured with speech-coil movement blocked (henrys)*

u_c = *speech-coil velocity (m/sec)* = e/Bl *where e is the counter e.m.f.*

B = *steady air-gap flux density (gauss) (weber/m²)*

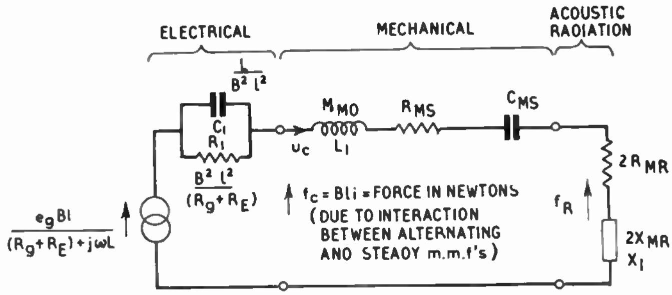
l = *length of wire on the speech-coil winding (m)*

M_{MD} = *mass of the diaphragm and the speech-coil (kg)*

C_{MS} = *total mechanical compliance of the suspensions (m/newton)*

R_{MS} = *mechanical resistance of the suspensions (mechanical ohms)*

u_c/f_c = *mechanical mobility* = Z_{MM}



$B^2l^2Z_{MM}$ = *motional electrical impedance*

Z_{MR} = *mechanical radiation impedance (mechanical ohms)*

The power-available efficiency at medium and low frequencies is given by

$$PAE = \frac{800\, B^2l^2R_gR_{MR}}{(R_g + R_E)^2(R_M{}^2 + X_M{}^2)}$$

Fig. 4.—Electro-mechano-acoustical circuit for frequencies below cone break-up (After Beranek[2]).

nevertheless it can be of inestimable help in research and design. Fig. 4 shows an electro-mechano-acoustical circuit (suitable for the following explanations) for a direct-radiator moving-coil loudspeaker mounted on an infinite baffle, and as far as can be judged from experience, the circuit is approximately correct for frequencies where the coil and cone move substantially as a whole.

Consider first the low-frequency region, bearing in mind that in practical modern 15-in. loudspeakers the permanent magnet will have a lower limit of 10,000 gauss (1 weber/m²) and an upper limit of about 13,000 gauss, these limits being set by reasons of efficiency and cost. The circuit shows that in the region around the frequency of bass resonance the output is almost entirely dependent upon the internal impedance of the amplifier. The circuit also disposes of the belief that the flux density materially affects the relative magnitude of response at resonance. Fig. 5 shows response curves obtained by solving the circuit. With all modern feedback amplifiers the output around the bass resonant frequency will be depressed below the middle-frequency level, due to the radiation impedances facing the loudspeaker, since $X_M = 0$ and the power output is determined by the total resistance in the circuit. The bottom curve shows the nature of the response. The middle curve shows the usefulness of the added back radiation available from a bass reflex cabinet. The top curve shows the type of response obtained from a pentode output stage without feedback. Fig. 4 shows that in the region above the bass-resonant frequency the radiated acoustic power tends to remain constant in value because both R_{MR} and $X_M{}^2$ vary as the square of frequency, and the frequency variation therefore cancels out, and thus cancels the fall in velocity due to mass control. Referring to the equivalent circuit for the higher frequencies it can be seen there is a possibility of a second resonance taking place.

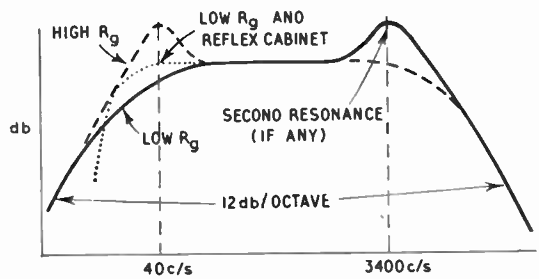


Fig. 5.—Theoretical graph of the power-available efficiency of a direct-radiator loudspeaker in an infinite baffle—with particular reference to 15-in. loudspeakers (After Beranek[2]).

the responsible circuit parameters being L/B^2l^2 and $M_{MD}+(X_1/\omega)$. It can be seen from the equivalent circuit that the condition for resonance is:

$$\frac{\omega L\,(B^2l^2)}{\omega^2L^2+(R_g+R_E)^2}=\omega M_{MD}+2\,X_{MR}$$

To maintain this condition ω^2L^2 must be greater than $(R_g+R_E)^2$. On the other hand, if ω^2L^2 is less than $(R_g+R_E)^2$ the reactance of C_l and R_1 works out to be a negative inductance, and there is no second resonance. The following data apply to the 15-in. moving-coil loudspeaker marked "A" on Fig. 3:

$B\cong 10{,}000$ gauss = weber/m²
$R_g\cong 0{\cdot}5\,\Omega$
$R_E\cong 12{\cdot}5\,\Omega$
$M_{MD}\cong 0{\cdot}048$ kg
$X_{MR}\cong 1{\cdot}26$ newton.sec/m
$L\cong 5\times 10^{-3}$ H
$l\cong 20$m

Hence
$\omega^2L^2\cong 9000$
$(R_g+R_E)^2\cong 169$

Solving the circuit with these practical values shows that the high-frequency resonance should occur at 3,400 c/s. Reference back to Fig. 3 shows that there is good correlation between response measurements and the results computed from the equivalent circuit. Notice that on the response curve of Fig. 3 resonance does not reach its peak exactly at 3,400 c/s, as expected according to calculation, and this is because the diaphragm is breaking up, which can be proved by watching the patterns made when the diaphragm is dusted with lycopodium powder.

It is seen, then, that the circuit can predict with good accuracy the performance of typical loudspeakers in the low-frequency region around resonance, in the middle-frequency region, and with fair accuracy in the region of high-frequency resonance. There is, however, one significant characteristic which this circuit has not explained, and that is the dip in the frequency response curves at just over 1,000 c/s. The dip is not explained because the analogue is not complete, for it does not allow for the fact that the velocity of propagation of sound in the paper cone is approximately twice the velocity of sound in air. The wavelength corresponding to 1,000 c/s in air is approximately 13 in., and the distance between the coil-former and the edge of the cone is $6\frac{1}{4}$ in. (see A in Fig. 3), that is, approximately half a wavelength. Sound propagated from the area near the coil will arrive at the periphery of the cone a quarter wavelength out of phase with the sound from the edge of the cone, and hence there will be partial cancellation, which explains the dip in the response curve. This explanation should emphasize two unfortunate characteristics of moving-coil cone loudspeakers. First, the regrettable shape, and second, the fact that because the cone is driven by the annular coil from the neck there must be travelling waves in the cone material. Further consideration of these travelling waves points to the possibility of their being reflected back when they arrive at the periphery, so causing reinforcements and cancellations in the sound output.

4.2. *Performance of Practical Moving-coil Loudspeakers*

Figure 6 shows the response of the two loudspeakers, "A" and "B," to square wave inputs. These are tracings from the microphone

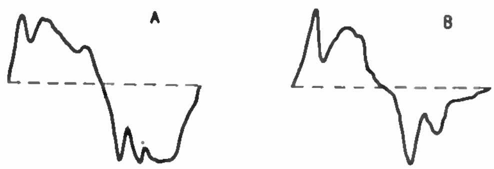


Fig. 6.—Response of loudspeakers of Fig. 3 to 500 c/s square wave.

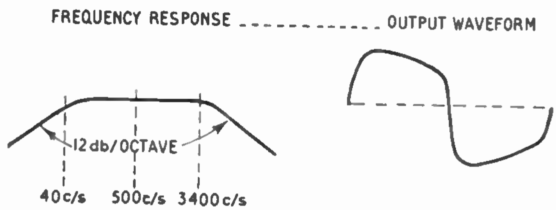


Fig. 7.—Response of idealized 15-in loudspeaker to 500 c/s square wave.

oscilloscope. In each case the positive and negative half-cycles are not symmetrical; the author has traced these asymmetries as being the result not only of asymmetrical suspension compliances, but to inherent asymmetric stiffness of the cone to "push" and "pull" forces, a factor previously unmentioned in the literature. It should be noted that a perfectly reproduced square wave is an impossibility, because all loudspeakers attenuate below the

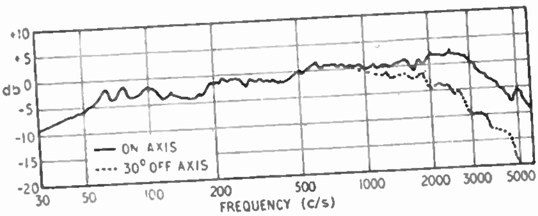


Fig. 8.—Response of an improved 15-in. loudspeaker.

bass resonant frequency and above the treble resonant frequency, but on the assumption that the axial response is flat within practical limits the waveform of Fig. 7 has been computed to show the ideal output for a square wave with a repetition frequency of 500 c/s.

It has been found possible to obtain a much flatter response than from the above examples by employing novel materials and constructions, and Fig. 8 shows the response curve of an improved 15-in. loudspeaker. It is seen that the response is relatively level on the axis up to 3,000 c/s, and for the curve for 30 deg. off the axis the response is level to 1,500 c/s. Fig. 9 shows the square wave response of this loudspeaker.

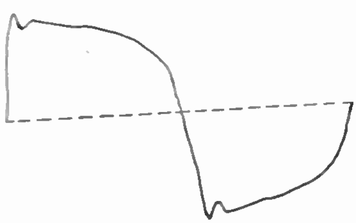


Fig. 9.—Improved bass loudspeaker : response for 500 c/s square wave.

Non-linear distortions in loudspeakers of this size are kept to a minimum by employing a speech-coil which is considerably longer than the magnetic gap, and by having suspensions which are not only compliant but which are equally compliant in both directions. With regard to suspensions at the periphery (surround) the author has no hesitation in stating that for the best results a paper extension of the cone should not be used—the only point in its favour is its cheapness. Its great disadvantage is that it radiates sound, and it can be proved by powder investigations that within the pass-band the surround will move in peculiar modes, and, at some frequencies, out of phase with the main body of the cone. A paper surround is also an unsuitable termination because it allows waves to be reflected back from the periphery towards the coil. These disadvantages tend to give an irregular frequency response characteristic and a poor transient characteristic to cones which are terminated with a paper surround. However well such a suspension may be designed, and however well it may be damped, better results can always be obtained in practice by the use of some other particular surround material.

4.3. *High-frequency Moving-coil Loudspeakers*

In view of the foregoing investigation we shall not need to go into as much detail when considering moving-coil direct-radiator high-frequency loudspeakers, because the problems are similar, though the scales of frequency and size are different. If, as a practical example, a 15-in. loudspeaker will reproduce satisfactorily up to 1,000 c/s, then when considering a "tweeter" to take over from 1,000 c/s a diaphragm diameter of approximately 4 in. will be needed. This diaphragm can be suspended so that low-frequency resonance occurs an octave or more below 1,000 c/s. The diameter of the diaphragm has to be 4 in. so that the cone will radiate enough sound at 1,000 c/s. Similarly it has to be stiff enough not to break up at 1,000 c/s. It therefore has a certain mass, and since the speech-coil also has mass, such a practical loudspeaker will have its high frequency resonance not higher than, at best, 5,000 c/s. This, then, is the high frequency limit and such a tweeter will not achieve high-fidelity reproduction if only for this restriction in frequency range.

The measured frequency response characteristics of two typical loudspeakers of this type are shown in Figs. 10 and 11; the effective diaphragm size of the circular loudspeaker is 4 in. and of the elliptical speaker 5 in. × 3 in. There is similarity between these two curves, and high-frequency resonance appears to take place at around 5,000 c/s. The axial response at resonance would be greater if the cone were stiffer, and the fact that the cone breaks up is responsible for the irregularities in the curves. A cone break-up pattern is shown in Fig. 12. The white lycopodium powder has collected on those regions which are not moving with as great an amplitude as the regions which show up black, the latter being the surfaces of the

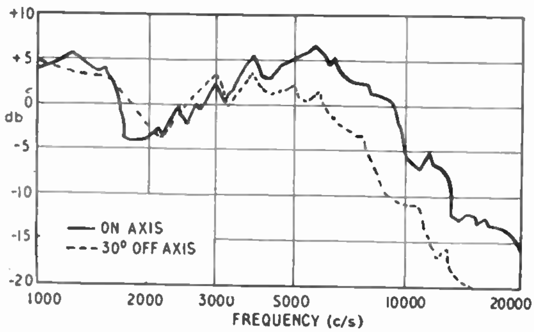


Fig. 10.—Response of 5-in. high-frequency loudspeaker ("Tweeter") with aluminium coil.

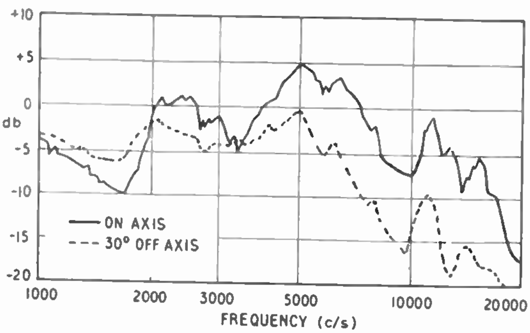


Fig. 11.—Response of 6 in. × 4 in. elliptical "tweeter": aluminium coil.

cone which are moving at greater amplitude and which have vibrated the powder away from them. Investigation with two small probe microphones will show that some parts of the cone are moving out of phase.

If we try to make a cone stiffer without reducing its size, its thickness and therefore weight must be increased so that the loudspeaker's sensitivity will be lowered. Reducing the size of the diaphragm in order to make it stiffer, will again lower the sensitivity because it will then not move enough air to be an efficient radiator unless it is coupled to a horn. This is the reason why horn tweeters are made and why they have a flatter frequency response, when well designed, than direct-radiator cone loudspeakers. It is important to realize that the sharp hills and valleys in the response curves of Figs. 3, 10 and 11 have been proved to be indicative of a poor response to transient signals and a slow decay time. A paper by Corrington[3] on the correlation of transient measurements on loudspeakers with listening tests proves this point. To sum up, moving-coil direct-radiator high-frequency loudspeakers have an irregular and restricted frequency response and a poor transient response because the moving parts are too large, too heavy, and not stiff enough. The most important aspect of the lack of stiffness is that the mechanical driving force originating at the speech-coil is mechanically remote and mechanically de-coupled from the main area of the radiating diaphragm. The movement of the diaphragm is therefore not completely controlled by the electrical signals delivered to the coil; hence the distortions in the sound output.

5. Ribbon Loudspeakers

The only type of moving-coil loudspeaker which does not possess the above inherent faults to anything like the same degree is the ribbon loudspeaker. This has a mode of operation essentially different from cone loudspeakers because the mechanical driving force is applied evenly, or nearly so, over the whole area of the diaphragm. It can be appreciated from Fig. 13 that this diaphragm is extremely light, being made of foil 2 in. × $\frac{3}{8}$ in. and only a fraction of one-thousandth of an inch thick. The diaphragm is actually the moving-coil and will obviously not be infinitely stiff. Now, this is a very important point indeed: the diaphragm does not need to be infinitely stiff because it is

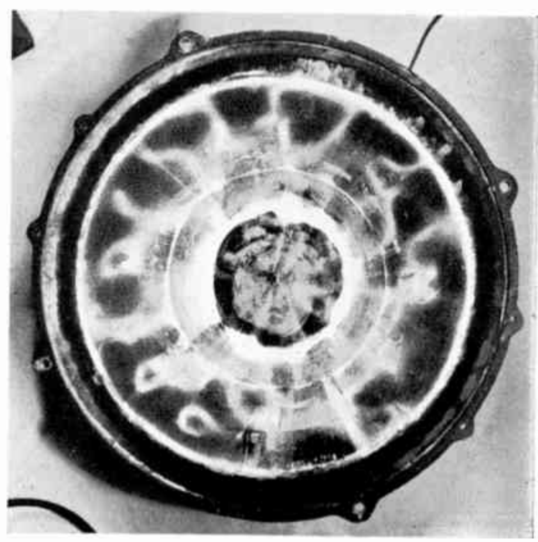


Fig. 12.—Cone break-up pattern.

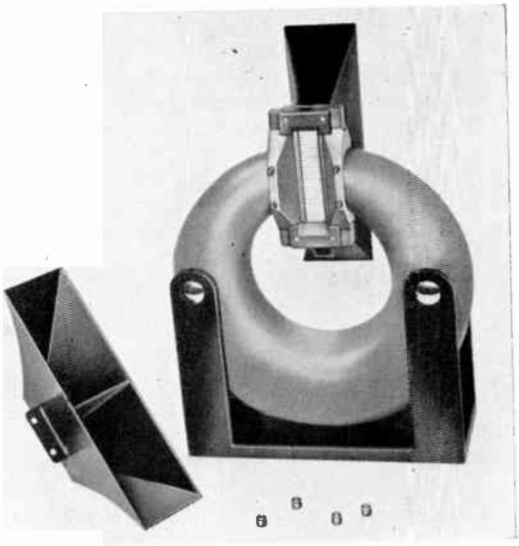


Fig. 13.—"Leak" ribbon loudspeaker.

forced to move by the electrical signal *as if it were* infinitely stiff. It really is important to grasp the fact that we are no longer attempting the impossible; we are no longer attempting to make a diaphragm infinitely stiff, and we no longer have travelling waves in it.

Figure 14 shows the frequency response of the ribbon loudspeaker illustrated in Fig. 13. The relative smoothness of the response is indicative of a good transient response. In the author's opinion the ribbon loudspeaker has been the most faithful transducer available in the past though it has not come into wide use because of some limitations. Because the area of the ribbon is small, and because its amplitude of movement is small, the ribbon loudspeaker must employ a horn in order to move an appreciable amount of air. In this particular loudspeaker the horn is small to ensure that the frequency response off the axis is well maintained. This ribbon loudspeaker has its lower cut-off frequency at 3,000 c/s, and this means that it will not be entirely suitable for use in conjunction with a 15-in. bass loudspeaker unless a third loudspeaker is interposed to cover the octave from 1,500 c/s to 3,000 c/s. This solution is rather costly and cumbersome, and for these and other reasons the model has not gone into production.

It appears from the above considerations that it would be desirable to have a system similar to the ribbon system in its essential of a light diaphragm forced to move as a rigid whole, but having a diaphragm many times the area so that it can radiate directly without a horn. This is impracticable by stepping up all the dimensions of the ribbon "tweeter," for the magnet would be of great size, weight and cost. However, there is another way of electrically forcing a very light, flexible and large diaphragm to move as a whole—the electrostatic loudspeaker.

6. Electrostatic Loudspeakers

Electrostatic loudspeakers have been under development for some thirty years, but have not been generally acceptable because of their performance limitations. Comparatively recently these limitations have been largely removed by the development of new materials and techniques, coupled with the conception of new ideas. It will greatly help us to grasp the significance of these developments if we consider the basic form of the earlier electrostatic loudspeakers.

6.1. *The Single-sided Electrostatic Loudspeaker*

A typical single-sided electrostatic loudspeaker is shown, with its associated circuit, in Fig. 15. The isolating capacitor merely serves to prevent the transformer short-circuiting the polarizing potential applied across the rigid plate and the flexible foil which comprise the actual electrostatic transducer. The high resistance may be several megohms in value because negligible current is drawn from the polarizing source by the loudspeaker, which can be seen to be a capacitor. This resistor also prevents the transformer being loaded by the

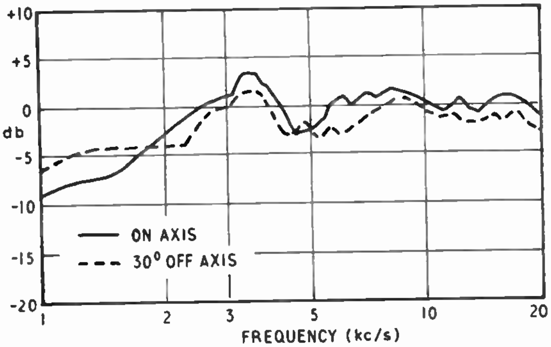


Fig. 14.—Frequency response of ribbon loudspeaker illustrated in Fig. 13.

source impedance of the polarizing voltage. This voltage will be several hundred volts or more, and in practice will be derived from a power supply unit, though for simplicity a battery is shown in Fig. 15. The air-gap between the plates, and the area of them, will be related to the lowest frequency which the loudspeaker is expected to reproduce efficiently.

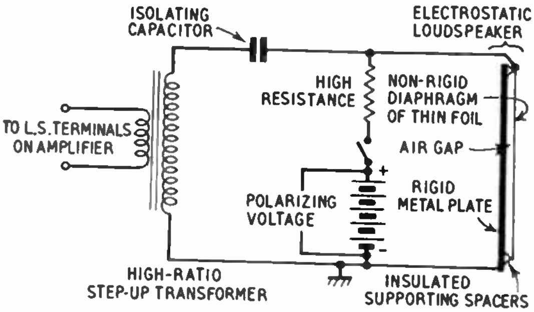


Fig. 15.—Schematic drawing of single-sided electrostatic loudspeaker.

A few square inches may suffice to cover the range from 8,000 c/s upwards, but to extend the range downwards to 1,000 c/s may require a square foot or more. Whatever may be the dimensions and spacing of the plates, the capacitance between them can be measured or calculated. This value gives the impedance range of the loudspeaker, which behaves as a capacitive reactance. A step-up transformer can thus be designed to give "optimum" matching between amplifier and loudspeaker.

Considering the modes of behaviour of the single-sided electrostatic loudspeaker, we first assume that the high-ratio step-up transformer is temporarily disconnected from the amplifier. If the polarizing voltage is now switched into circuit a potential will build up across the rigid plate and the diaphragm, and the resulting electrostatic force of attraction will cause the thin diaphragm to move towards the rigid plate. If this flexible diaphragm is not constrained, as by stretching, it will obviously move into contact with the rigid plate. If the diaphragm is tensioned sufficiently to prevent this collapse, then it will take up a position of equilibrium whose location with respect to the rigid plate will be determined by the ratio of the forces contributed by the polarizing potential (towards collapse) and the diaphragm tension (against collapse). Hunt has shown[4] that to ensure stability the diaphragm must not be pulled towards the fixed plate more than a quarter of the distance which separated them before the application of the polarizing voltage. If the high-ratio step-up transformer is now connected to the amplifier the electrical signals from the latter will cause the diaphragm to move back and forth about the equilibrium position, so producing a sound output.

The degree of faithfulness of this sound output depends on how accurately these backward and forward movements duplicate mechanically the positive and negative half-cycles of the electrical signals which cause them. It can be shown, experimentally and theoretically, that the degree of duplication is poor, that is, the distortion in the sound output is high, unless the amplitude of movement of the diaphragm is kept very small. This amplitude restriction means that the sound output is small, and the loudspeaker is therefore *effectively* too inefficient to be of practical interest. There are also other disadvantages arising from these older constructions. First, the layer of air trapped between the diaphragm and the rigid plate adds to the non-linearity of frequency response of the system: next, temperature changes will affect the tensioning of the thin foil diaphragm; a drop in temperature will stiffen it, and a rise may expand it sufficiently to cause the polarizing potential to arc across the reduced air-gap. Furthermore, chemical reactions are likely in some climates when very thin aluminium foil is exposed.

To sum up, the single-sided electrostatic loudspeaker does not appear desirable as a high-fidelity reproducer, certainly when expected to reproduce over a wide frequency range, and this conclusion has been confirmed by every engineer labouring on the project. But the theoretical attractiveness of having a uniform drive over a large diaphragm area has ensured that many engineers have thought deeply and worked hard on these problems, and as the result of many years' development there has been evolved a form of modern electrostatic loudspeaker whose performance is markedly superior to that of other types. We will jump the slow progressive stages of its evolution and proceed to examine the basic form of the balanced push-pull electrostatic loudspeakers recently developed.

6.2. *The Balanced Push-pull Electrostatic Loudspeaker*

It will be seen that the circuit of Fig. 16 bears some resemblances to the last one. There is still the high-ratio step-up transformer, the high polarizing voltage, and the high resistance, but the actual loudspeaker elements are quite different, and their basic features are as follows:

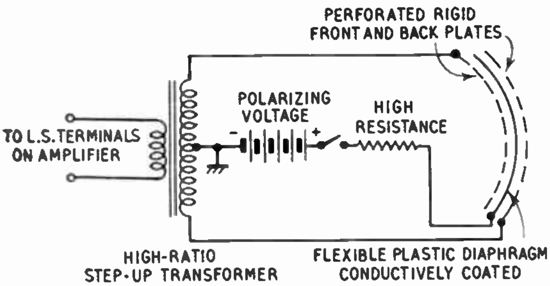


Fig. 16.—Schematic drawing of balanced push-pull electrostatic loudspeaker.

First, the thin flexible diaphragm is no longer a sheet of foil, but a sheet of extremely tough plastic material having a negligible temperature co-efficient of expansion, which is coated with a conducting material so thin that it does not materially add to the weight of the diaphragm. The thickness of the diaphragm is a fraction of one-thousandth of an inch.

Second, the thin diaphragm is held by a system of insulating spacers equidistant between two rigid plates. These plates are acoustically transparent, that is, they allow sound waves to pass through them unimpeded.

Thirdly, the whole assembly is formed into an arc in the horizontal plane (Fig. 17).

Now, if one changes from a single-sided amplifier to a push-pull amplifier there are appreciable improvements in distortion and power output, but when one changes from a single-sided electrostatic loudspeaker to the balanced push-pull type it would, as Hunt says, "be an understatement to say that the improvements are appreciable: they are indeed spectacular." Assume for the moment that the transformer is disconnected from the amplifier. When the polarizing voltage is switched into circuit the diaphragm will not move, because it is subjected to equal and opposite electrostatic forces from each plate. This means that the diaphragm need not be stretched to resist the static forces, thus removing one cause of the non-linearities inherent in the single-sided loudspeaker previously discussed. Furthermore, if the diaphragm is moved towards one plate it does not upset the condition of equal and opposite forces acting on it provided that the charge is maintained, and this can easily be ensured by making the resistance in series with the diaphragm of sufficient magnitude to give a long time-constant.

This resistor also fulfils another very important function—that of controlling the amplitude of the second harmonic distortion. When considering the structure of this balanced push-bull loudspeaker one can envisage that, in practice, it will be difficult to maintain exact symmetry. One capacitor will be of greater value than the other, and the capacitor which is greater will tend to behave in much the same way as a single-sided electrostatic loudspeaker. It will be non-linear, with a tendency to generate second harmonic distortions. Hunt carried out experiments to determine the magnitude of the distortions in relation to capacitance unbalance between the two sides, and to determine how the magnitude of the second harmonic distortions varied with the value of the series resistance. Two of the conditions of the test were particularly stringent.

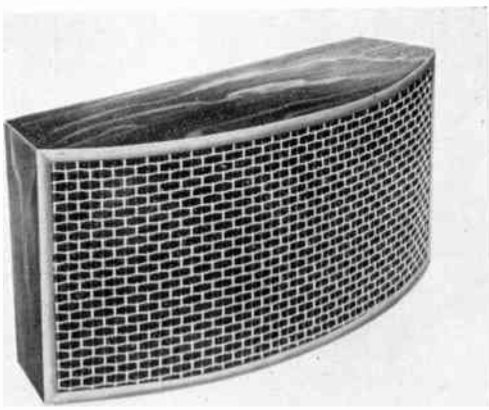


Fig. 17.—The author's high-frequency electrostatic loudspeaker.

First, he chose a relatively low fundamental frequency of 170 c/s so that the amplitude of the diaphragm motion would be substantial. Next he made the peak alternating voltage on

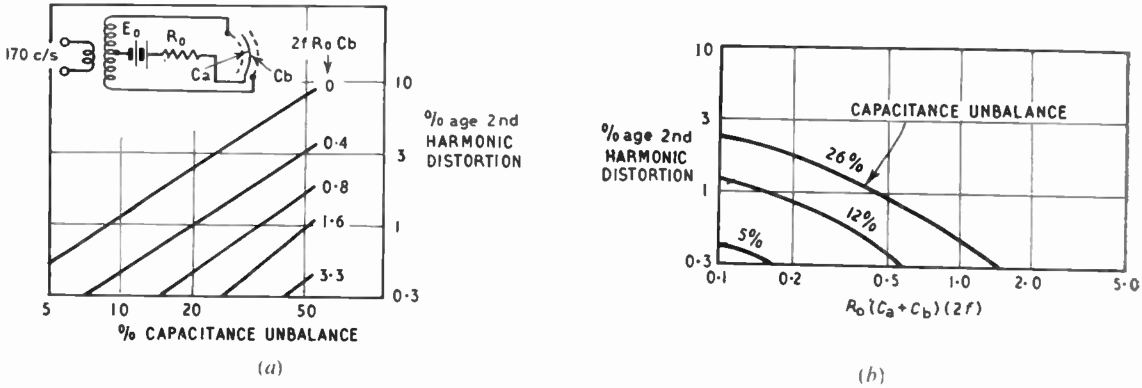


Fig. 18.—Relation of capacitance unbalance, time constant and distortion (After Hunt[5])

each half of the push-pull unit 10 per cent. higher than the d.c. bias voltage. The electrostatic speaker on which these tests were made was relatively small. It had a diameter of about 5 in. and it was so arranged that one of the spacings could be altered to allow the degree of capacitance unbalance to be varied.

Figure 18 shows Hunt's results, and very astonishing they are. The base of Fig. 18a is the percentage capacitance unbalance. The graph shows how the magnitude of second harmonic distortion is progressively reduced as the series resistor is increased. The appropriate measure of this resistance is the quantity $2fR_0C_0$, which is the ratio of the time-constant of the charging circuit to a half-cycle. In practice, it is not difficult to construct balanced push-pull electrostatic loudspeakers with differences as small as 10 per cent. capacitance unbalance, and one may therefore gauge from the graph that by increasing the series resistor one can get down to extremely low distortions—distortions of 0·1 of 1 per cent. Much the same data is used in Fig. 18b in which is shown the second harmonic as a function of the time-constant ratio with the capacitance unbalance as a parameter. Hunt's experiments and his theoretical analyses show that the magnitude of each order of distortion will be lower than the preceding one, hence the third harmonic will always be less than the second (rather a surprising result from a push-pull circuit!). As regards transient distortion, this balanced push-pull type of construction may be expected to give better transient response than any other form of loudspeaker, with the possible exception of the Ionophone,[7] which is an inertia-less gaseous discharge device. The frequency response of this type of electrostatic loudspeaker, with its smooth and gentle undulations, confirms the impression that the transient response will be extraordinarily good, and Corrington has confirmed that a similar type of balanced push-pull electrostatic loudspeaker gave transient decay measurements greatly superior to those of any other loudspeaker tested in the R.C.A. Acoustic Laboratories.[3]

The high frequency response is well maintained off the axis (Fig. 19) on the horizontal plane because of the curved construction, but in the vertical plane the response will be more directional.

The acoustic output from this type of balanced push-pull loudspeaker is of the same order as from conventional cone loudspeakers. Its sensitivity is therefore satisfactory, in direct contrast with the single-sided system.

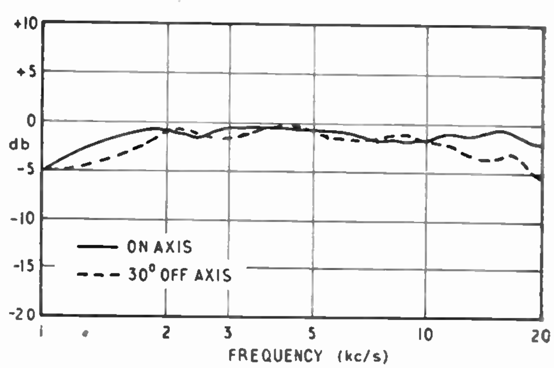


Fig. 19.—Frequency response of the balanced push-pull electrostatic tweeter of Fig. 17.

As regards reliability, there is no difficulty with presently available materials in constructing electrostatic loudspeakers operating from 1,000 c/s upwards, and freedom from breakdown appears to be of the same order as with moving-coil types.

As regards cost, an electrostatic high-frequency loudspeaker of this type will cost about £20, including its housing, polarizing potential, and built-in 1,000 c/s crossover network to match the 15-ohm low-frequency speaker, which will also cost about £20 (without cabinet).

7. Conclusions

At present the author cannot produce an electrostatic bass loudspeaker having *both* the necessities of reasonable size and great reliability. This is because materials of suitable form and physical properties have not yet been made. The problems are technological, and they will be solved in time—probably within a year.

During this period the author expects to show: (1) that electrostatic bass loudspeakers will *not* take the form represented diagrammatically by Fig. 16, and (2) that it will be logical to integrate the loudspeaker transducer with the power amplifier as a single unit which will be driven remotely by a small control pre-amplifier.

To sum up, the author believes that imminent developments in electrostatic loudspeakers will result in as great an advance in listening quality as occurred with the advent of the Rice-Kellogg moving-coil loudspeaker in 1925, and with the author's introduction of very low-distortion amplifiers in 1945.

8. Acknowledgments

The author would like to pay tribute to those fellow engineers, and to those mathematicians and physicists, who have helped to advance our knowledge in this fascinating and difficult subject. The author would particularly like to thank his colleagues, Edward Ashley and Ananta Sarkar, M.Sc., for their invaluable help during the research and development programme on which this paper is based.

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APPLICANTS FOR MEMBERSHIP

New proposals were considered by the Membership Committee at a meeting on 15th November, 1956, as follows: 49 proposals for direct election to Graduateship or higher grade of membership, and 30 proposals for transfer to Graduateship or higher grade of membership. In addition, 75 applications for Studentship registration were considered. This list also contains the names of 23 Students registered at the meeting on 4th October; the names of 35 transfers and elections to Graduateship will be given in the next list.

The following are the names of those who have been properly proposed and appear qualified. In accordance with a resolution of Council and in the absence of any objections being lodged, these elections will be confirmed 14 days from the date of the circulation of this list. Any objections received will be submitted to the next meeting of the Council with whom the final decision rests.

Transfer from Associate Member to Member

HOWELL, Edwin Charles. *Slough.*

Direct Election to Associate Member

BERG, Leonard. *Ilford.*
EATON, John Lomas, B.Sc. *Radlett.*
GEE, Walter William Cecil. *Twickenham.*
HARMAN, Reginald Richard. *Wembley.*
McEWEN, Lt.-Col. John Alastair Douglas. *Shrivenham.*
MOUGHTIN, Thomas Edward Frederick. *Bridport.*
SHERWIN, Kenneth. *Swindon.*
TRAFFORD, Gilmore Henry. *Hayes, Middlesex.*
TURNER, Frederick Charles. *Braintree.*

Transfer from Associate to Associate Member

COLLINSON, Thomas. *Malmesbury.*
SPRING, Hans Paul. *London, S.E.3.*

Transfer from Graduate to Associate Member

COOPER, Ernest, B.Sc. *Cambridge.*
GIFKINS, Geoffrey Charles. *Hertford.*
GREEN, Arthur Eric, B.Sc. *Wirral.*
LOVELL, Peter Gareth, B.Sc. *London, W.3.*
McILWRAITH, John Wallace Breckenridge. *Portsmouth.*

Transfer from Student to Associate Member

FRANK, Erich Jehuda. *Rehovoth, Israel.*
ROBERTS, William Edward, B.Sc.(Eng.). *Plymouth.*
SAMUEL, Duncan Roy. *Cardiff.*

Direct Election to Associate

ASHWORTH, Capt. Walter Hedley, R.A. *Larkhill, Wilts.*
FAWCETT, Sqdn. Ldr. Elgar Arnold, R.A.F. *Isleworth.*
FIELD, Terence Owen. *London, S.E.4.*
HARRISON, Victor Albert Wilfred. *Shepperton.*
PATTERSON, Robert. *Great Malvern, Worcs.*
ROGERSON, Charles Stephen. *Altrincham.*
STUNELL, Anthony Gordon. *Arborfield.*
THOMAS, Daniel Jallow. *Ain Zalah, Iraq.*
YOUAKIM, Mansour Francis. *Amman, Jordan.*

Transfer from Student to Associate

DUBGOTRA, Diwan Chand, B.Sc. *Balurghat, West Bengal.*

STUDENTSHIP REGISTRATIONS

Registered on 4th October:

NEWMAN, Martin Myer. *Emek Bet Shean, Israel.*
O'HORA, Nathy Patrick J., B.Sc. *Dorking.*
PACKER, Flt. Lt. David Geoffrey Lawson, B.Sc.(Hons.), R.A.F. *Henlow.*
PALMER, Leonard Sidney. *London, S.W.20.*
PANDYA, Niranjan J. *London, N.W.11.*
PHILLIPS, Brian. *Harrow.*
RAMBRIDGE, Robert. *London, W.14.*
RICH, Hubert John. *London, W.2.*
ROMAINE, David Albert F. *London, W.5.*
RYDER, Geoffrey. *Dagenham.*
SILLS, William Henry A. *London, E.11.*
SIMMANS, Albert Frederick G. *Ilford.*
SOOD, Balbir Sagar. *Mathura.*
STANTON, Frederick Joseph. *Nazeing, Essex.*
STIVAROS, George. *Limassol.*
TAYIM, Mohamed Abdulkader. *Limassol.*
TIN-TUN, Maung, B.Sc. *London, S.W.13.*
TO, Albany Shiu-Kin. *Kuala Lumpur.*
TUCKER, Allan Arthur. *Sutton Coldfield.*
WALKER, Rainer George. *Toronto.*
WALTERS, Arthur John. *Bristol.*
YADAVA, Om Prakash Singh. *Bangalore.*
ZARNOSWKI, Zygmunt. *Perth, W. Australia.*

Registered on 15th November:

AGARWAL, Prakash Chand. *Agra.*
AGARWAL, Vishwa Nath. *Jullunder City.*
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* Reinstatement

GRID CONTROL OF THYRATRONS WITH PARTICULAR REFERENCE TO SERVO-MECHANISM APPLICATIONS*

by

K. R. McLachlan (Associate Member)†

SUMMARY

A brief review of existing methods and their limitations is followed by a description of what is believed to be a new approach to the problem of thyratron control. This approach enables a linear control of firing point to be achieved over the whole range from 0–180 deg. and details of a practical circuit are given together with some experimental results.

1. Introduction

The use of thyratrons for the control of motor speed is well known and the circuits for biasing their grids to obtain the required control are many and varied. These circuits fall into one of two broad categories: those in which the control is effected by mechanical movement and those in which it is brought about by an electrical signal.

In the first category come such methods as phase control of an alternating signal applied to the thyratron grid by means of a phase-shifting transformer or by means of a CR phase-shifting network. These methods give excellent control, from zero to maximum of the thyratron anode current as shown in Fig. 1, but require the rotation of a shaft or some other form of mechanical movement to vary the control voltage.

The second category contains methods in which the control is effected by the application of a voltage which either directly or indirectly varies the bias on the thyratron grid. An example of the direct method is that in which an alternating voltage is applied to the thyratron grid, the mean level of which is set by the control signal. For correct operation the alternating voltage must be 90 deg. out of phase with respect to the anode supply voltage as shown in Fig. 2. As an example of the indirect method that in which the alternating voltage is controlled in phase by means of a zero frequency voltage may be quoted. Here a CR phase-shifting circuit is employed in which the required variation of R is accomplished by employing the variation of anode resistance which takes place in a thermionic valve with change in grid voltage. A skeleton circuit of this method is shown in Fig. 3, together with

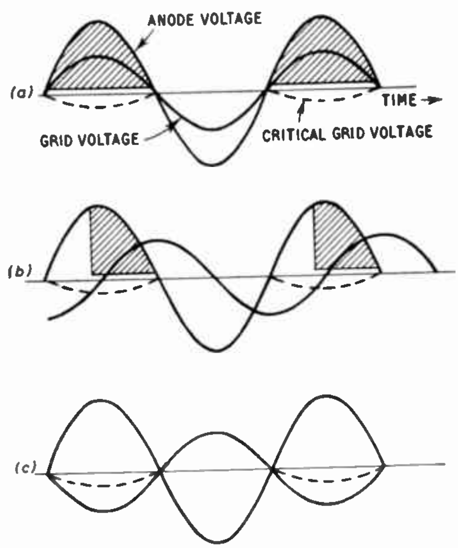

Fig. 1.—Voltage relationships for grid control of thyratrons using mechanically controlled phase-shifter.
(a) Grid voltage in phase with anode voltage.
(b) Grid voltage lagging by 90°.
(c) Grid voltage lagging by 180°.
Shaded areas represent voltage available to the load.

* Manuscript first received 20th December 1955 and in final form 21st November, 1956. (Paper No. 379.)
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U.D.C. No. 621.385.38:621.316.718.5

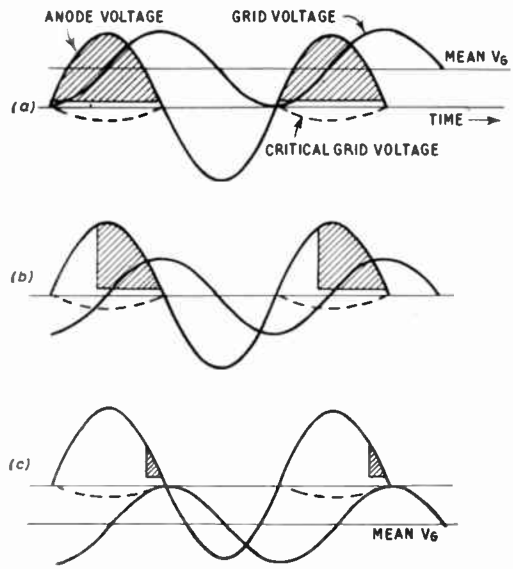

Fig. 2.—Voltage relationships for grid control of thyratrons by varying grid bias.
(a) Mean V_g = +Peak V_g.
(b) Mean V_g = Zero.
(c) Mean V_g = −Peak V_g
Shaded areas represent voltage available to the load.

the relationship between control voltage and phase which can be obtained in a carefully adjusted circuit.

2. Limitations of Existing Methods

From this brief review, the relative merits of the different methods for motor speed control applications may be assessed. The methods in the first category are quite satisfactory in cases where quasi-constant speed is required under steady load conditions. Changes in speed must be made by manual operation of the control shaft and the full range from zero to maximum speed is available. Where control of speed by velocity or other feedback signals is required, however, these methods are clearly unsatisfactory since such feedback signals are usually derived from a tachometer generator or similar device giving a voltage output.

To cater for such applications a method from the second category must be chosen so that the control and feedback signals may be combined to produce the required conditions. Closer investigation of these methods however shows that they have a number of limitations which reduce their range of usefulness. Referring to the method shown in Fig. 2, it will be seen that as the mean level of the sine wave is changed by the controlling signal, the effect on the anode current will be far from linear. In addition, the firing point will be dependent on the characteristics of the thyratron and as these will vary with time and temperature, the accuracy of control is correspondingly poor.

The method shown in Fig. 3 is also non-linear and in addition the maximum range of control which can be obtained is of the order of 130 deg. Hence, if the thyratron anode current is to be brought to zero by this means the maximum current cannot be achieved. Conversely, if the circuit is arranged so that a maximum anode current can be reached, the minimum current is not zero.

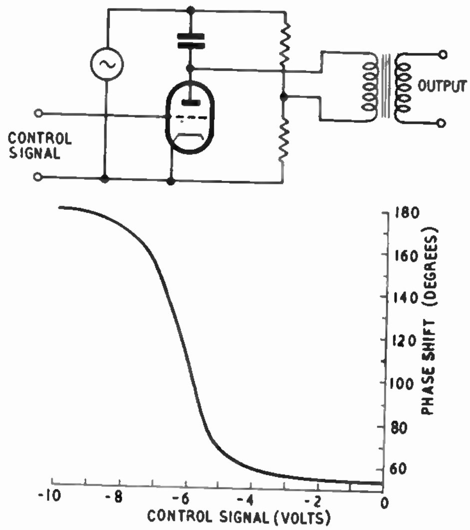

Fig. 3.—Phase shift by variation of the anode resistance of a valve.
(a) Skeleton circuit. (b) Typical control voltage/phase shift relationship.

3. Description of a New Method

To provide a method of control which is suitable for servo-mechanism applications where a number of feedback voltages may be required and where linear control of the firing point over the whole range from zero to maximum current is necessary, a new circuit has been devised. This circuit, a block diagram of which is given in Fig. 4, produces a steep-fronted control voltage at the thyratron grid and hence has the additional advantage of being sensibly independent of the characteristics of this valve.

The principle of operation of the circuit can be understood from the block diagram and from Fig. 5 which shows the voltage waveforms at various points in the circuit. A square waveform is produced from the 50-c/s supply mains by the limiting amplifier and fed to a

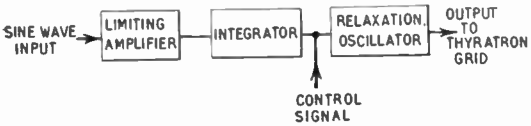

Fig. 4.—Block diagrams of the method described in the paper.

simple integrating circuit. This results in a triangular waveform, the fundamental component of which is 90 deg. out of phase with respect to the sine wave input. The mean level of the triangular waveform is adjusted by the control signal and the resultant fed to the grid of the relaxation oscillator having a frequency of oscillation much higher than that of the supply mains. As this oscillator is inherently a trigger circuit, there is a critical grid voltage at which oscillations will commence and cease. Thus, if the grid voltage is more negative than this critical value oscillations will be inhibited, but if it is more positive continuous oscillations will be maintained. Referring to Fig. 5, it will be seen that if the mean level of the triangular waveform is adjusted to be equal to this critical voltage then the oscillator will function for one half of the supply cycle only. When the mean value of the triangular waveform is set such that the negative peaks just fail to reach the critical value, then continuous oscillations will be maintained. If, however, the postive peaks fail to reach the critical value, then the oscillator is completely suppressed. Between these limits there will be a linear relationship between the point in the supply cycle where oscillations start and the mean level of the triangular waveform.

The pulses from the relaxation oscillator are fed to the thyratron grid, driving it positive to initiate anode current. A steady negative voltage is also maintained at this grid to prevent the thyratron firing during periods when the relaxation oscillator is suppressed.

The need for a free running oscillator rather than a bi-stable trigger circuit can be seen by considering the case where the control signal has exceeded the peak value of the triangular waveform. Depending on the polarity of the control signal the oscillator will either be suppressed or continuously running and consequently the thyratron anode current will be zero or maximum. With a bi-stable circuit however, such a simple differentiation between the maximum and zero current conditions cannot be achieved.

This circuit then, enables the firing point of a thyratron to be controlled by a voltage and the relationship between this voltage and the firing point is linear over the whole range from 0 to 180 deg. In addition, due to the steep leading edge of the relaxation oscillator pulse,

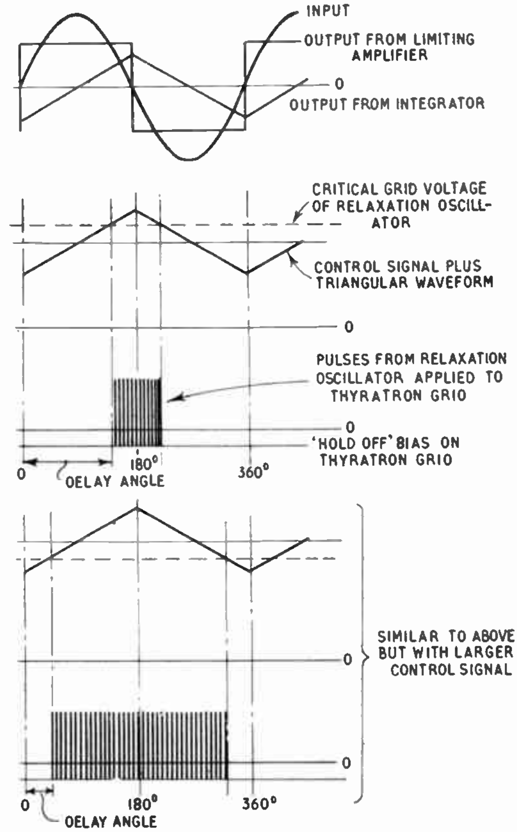

Fig. 5.—Voltage waveforms in circuit of Fig. 4.

this control is virtually independent of changes in the thyratron characteristics.

4. Practical Circuit

In practice the obvious advantages of operating two thyratrons in a full-wave rectification circuit are normally required and the prototype circuit outlined may easily be modified

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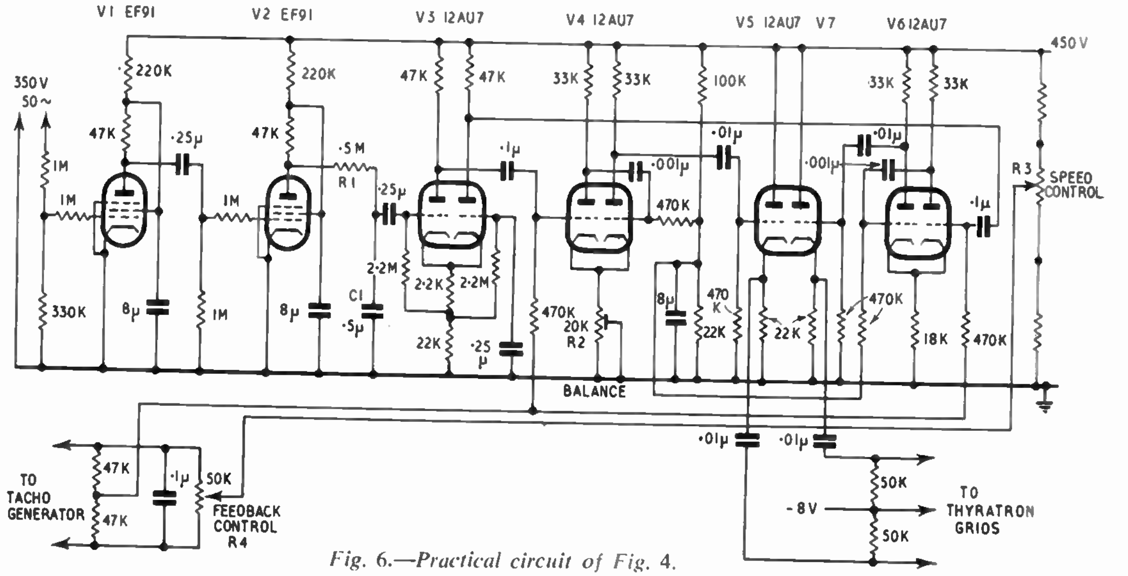

Fig. 6.—Practical circuit of Fig. 4.

to cater for such operation. A complete circuit diagram for controlling two thyratrons in this manner is given in Fig. 6. In the diagram V1 and V2 form the limiting amplifier which feeds a 50-c/s square waveform to the simple integrating circuit composed of R1 and C1. The triangular waveform appearing across C1 has a peak-to-peak amplitude of approximately 1 volt and is fed to one grid of the phase invertor stage V3. The gain from grid to each anode of V3 is approximately 10 and the in-phase signal from A_2 of this valve is applied via a capacitor to the quiescent grid of V4. The latter valve is connected as a cathode coupled relaxation oscillator having a repetition frequency of some 2,000 c/s. The mean level of the voltage at the quiescent grid of V4 is set by adjustment of R3 which forms part of a potential divider connected to the h.t. supply. Pulses from the relaxation oscillator V4 are applied to V5 connected as a cathode follower, which isolates V4 from the adverse effects of grid current in the thyratron. V5 also clips the negative part of the pulses and at its cathode provides positive pulses of 20 volts amplitude.

The valves V6 and V7 which have similar circuit function to V4 and V5 respectively are controlled by the anti-phase triangular waveform appearing at A_1 of V3, the mean level of which is set as before by adjustment of R3. Thus, there is a difference of 180 deg. between the commencement of pulses at the cathodes of V5 and V7 in each cycle of the supply frequency. By feeding the output from V5 and V7 to the appropriate grid of each thyratron the desired full wave operation is obtained.

The thyratrons (type MT57) obtain their anode supply from a transformer having a centre-tapped secondary capable of delivering 2·5 A at 500 V. Other circuits are also included in the unit to provide the constant voltage for the motor field, negative bias for the thyratron grids and to delay the switching of the anode supply during the warming up period of the thyratron cathodes.

A conventional d.c. shunt wound motor is used in conjunction with this control unit and its normal maximum output is 0·5 h.p. at 1.500 rev/min.

5. Control and Feedback Circuits

With the circuit described linear control of the firing point of the thyratrons over the range 0 to 180 deg. is achieved by adjustment of the voltage at the slider of R3. Current balance in the thyratron anodes depends on the firing point being identical for each valve. This is achieved by adjustment of R2 which enables the critical grid voltages of the two relaxation oscillators to be made identical.

In addition to the control signal derived from R3, a signal from a tachometer generator is also

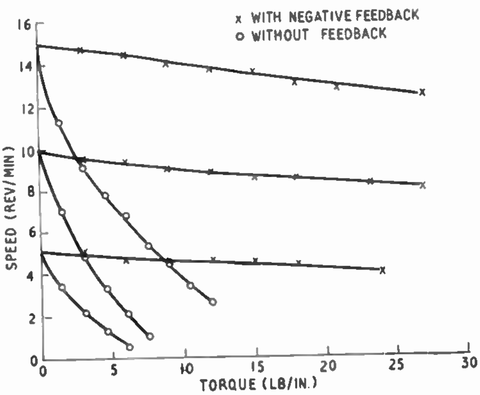

Fig. 7.—Typical speed/torque characteristics.

used. The signal derived from this generator is placed in series with the control signal and its magnitude and direction can be varied by adjustment of R4.

Thus, when the generator voltage opposes the control signal, negative velocity feedback is produced and any change in speed due to load causes the firing point of the thyratron to be adjusted in such a direction as to maintain the speed constant. This effect is analogous to the reduction of output impedance of an electronic amplifier due to the application of negative voltage feedback and the speed/torque characteristics shown in Fig. 7 are similar to the output voltage/load current characteristics of an amplifier. As in the amplifier case, the "output impedance" of the system cannot, in practice, be made zero by this means and some change in speed with load will always occur. The curves given in Fig. 7 however, show that when the negative feedback is maximum, the motor speed is constant within 10 per cent. over the whole load range.

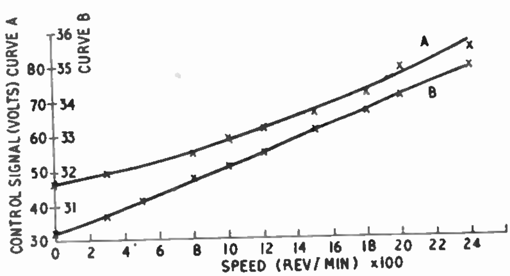

Fig. 8.—Control signal required for various motor speeds. (a) With no negative feedback; (b) with maximum negative feedback.

When the generator voltage assists the control signal, positive velocity feedback is produced and the "output impedance" is increased. Hence, by adjustment of R4, a wide range of speed/load characteristics may be obtained.

In addition, this circuit may easily be modified to work with other feedback signals to provide, say, constant current or constant voltage output conditions over a wide range. The control and feedback signals may also be modified by CR networks to give voltages that are proportional to the derivative or integral of these signals.

Two curves relating control signal voltage to motor speed are given in Fig. 8, the relationship with no negative feedback being given by curve A and that for maximum negative feedback by curve B. From these curves it can be seen that the inherent linearity of the system is good over the whole control range.

6. Application

The circuit described was developed for a particular application in which it was required to simulate the characteristics of an internal combustion engine and to add to these characteristics various forms of governor control. The governor may also be represented by electric circuits fed from a tachometer generator and the resulting signal applied in series with the control voltage. In this way the overall characteristics of the engine and governor may be simulated and the ease with which the various circuit parameters may be changed makes it possible to study the effect of combining a wide range of engine and governor characteristics.

Thyratron control of motor speed is particularly suitable for this application since, like the internal combustion engine, it is not possible to feed mechanical power back into the primary source of supply. Thus, when the input is reduced from one value to another, the speed drops in a manner which is dependent only on the mechanical energy stored, the total energy supplied to the load and the mechanical losses.

Although the circuit given is more complicated than those normally used for thyratron control, the advantages of linearity, range and flexibility outweigh the disadvantage of increased complication. In addition, the stability of performance of the circuit is high and in practice has proved to be much better than that of the circuit shown in Fig. 3.

The British Institution of Radio Engineers

NOTICE OF EXTRAORDINARY GENERAL MEETING

NOTICE IS HEREBY GIVEN that an Extraordinary General Meeting of the corporate members (Honorary Members, Members, and Associate Members) of the British Institution of Radio Engineers will be held at the London School of Hygiene and Tropical Medicine, Keppel Street, Gower Street, London, W.C.1, on Wednesday, January 30th, 1957, at 6 p.m., for the purpose of considering and if thought fit passing with or without amendment the subjoined resolution as a Special Resolution.

RESOLUTION

That the Articles of Association contained in the printed document laid before this Meeting and subscribed for identification by the President be and the same are hereby adopted as the Articles of Association of the Institution in substitution for and to the exclusion of its existing Articles.

A copy of this notice convening the meeting, together with the proposed new Articles of Association, is being circulated to corporate members. The alterations are unanimously recommended by the General Council as a result of proposals made by the appropriate Committees and referred to in successive Annual Reports of the Institution.

The Council also wishes to take this opportunity to bring the Articles of Association into line with the provisions of the 1948 Companies Act. The existing Articles have, with few amendments, been operative since the incorporation of the Institution in 1932.

The proposed alterations also provide for the use of the word "Institution" instead of "Institute" consequent upon the change of name of the Institution in 1941, and for full expression to be given to the objects of the Institution by the use of the term "electronics" following the alterations to the Memorandum of Association sanctioned in 1945.

Adoption of the new Articles will also give effect to the new subscription rates sanctioned at the Annual General Meeting held on October 31st, 1956.

By Order of the Council,

G. D. CLIFFORD,

General Secretary.

December 20th, 1956.
9, Bedford Square.
London, W.C.1.

SUBJECT INDEX

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A list of Journals from which Abstracts have been taken during 1956

Archiv der Elektrischen Ubertragung (Germany); *Canadian Institute of Physics*; *Elektrotehniski Vestnik* (Yugoslavia); *Elettronica* (Italy); *Engineering Journal of Canada*; *Fernmeldetechnische Zeitschrift* (Germany); *Indian Journal of Physics*; *Journal of the Institution of Engineers, Australia*; *Journal of the Institution of Telecommunication Engineers* (India); *Onde Electrique* (France); *Philips Technical Review* (Netherlands); *Proceedings of the I.R.E., Australia*; *Teknillinen Aikakauslehti* (Finland).

Printed by F. A. Hunt & Son, Ltd., 126 Denmark Hill, S.E.5