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A Symposium on

"VIBRATION METHODS OF TESTING"

held by the Institution in London on December 9th, 1953.

Chairman: Mr. J. L. Thompson (Vice-President)

"Vibration Generators, Ancillary Equipment and Applications"—H. MOORE.

"Electronic Stroboscopes"—F. M. SAVAGE.

"Resistance Strain Gauges and Vibration Measurement"—P. JACKSON.

"Electronic Aids to Vibration Measurement"—R. K. VINYCOMB.

INTRODUCTION

In discussing the 1954 Convention on Industrial Electronics, reference has already been made in the *Journal* to the fact that many members of the Institution are concerned with the applications of electronics to fields other than that of communication engineering.

Meetings have been held, both in London and in the Local Sections, devoted to papers on these topics and, in particular, to those which fall into the category of industrial electronics, and the success of such meetings has led to the formation of a specialized group within the Institution.

It is impracticable to cover all the many aspects of industrial electronics in the space of a four-day Convention; with this in mind the Programme and Papers Committee, in collaboration with the Industrial Electronics Group, arranged the Symposium on Vibration Methods of Testing. This particular facet of the electronic art concerns a varied range of industries: representatives of the aircraft, automobile, civil and mechanical engineering, metallurgical and chemical industries were present, as well as engineers from the radio industry and Government Departments. The interest taken in the Symposium by these industries demonstrates very clearly the increasing scope of electronics.

The four papers presented dealt with a limited part of the large and ever-expanding application of electronics to the field of testing equipment and components for their suitability in operation, and in his concluding remarks the Chairman, Mr. J. L. Thompson, referred to a statement by Lord Kelvin, nearly 100 years ago:

> "I often say that when you can measure what you are speaking about, and express it in numbers, you know something about it, but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind; it may be the beginning of knowledge, but you have scarcely, in your thoughts, advanced to the stage of science, whatever the matter may be."

Mr. Thompson said that the contributions to the Symposium proved that it was now possible to measure mechanical vibration. As a result of this advance in knowledge, the means of solving many difficult problems in a wide range of industries were available.

VIBRATION GENERATORS, ANCILLARY EQUIPMENT AND APPLICATIONS*

by

H. Moore†

Read at the Symposium on "Vibration Methods of Testing," December 9th, 1953.

Also read before the Scottish Section of the Institution in Edinburgh on November 5th, 1953.

SUMMARY

The application and theory of operation of the moving-coil vibration generator is described in terms of modern loudspeaker theory, particular stress being laid on the implications of the motional impedance diagram. Driving equipment including electronic oscillators, power amplifiers, and speed-controlled motor-alternator sets are also described. The applications of vibration generators to reliability testing and to the investigation of structures are discussed briefly.

1. Introduction

The study of vibration phenomena is generally regarded as the province of the mechanical engineer. The subject is, however, closely analogous with alternating current theory, and is therefore readily appreciated by the radio engineer. The familiar properties of the tuned circuit in the electrical sense can be conveniently related to the resonant mechanical system.

Modern methods of vibration testing and measurements, involve the use of electronic aids to such an extent that some considerable knowledge of electrical methods is essential to making the best use of the medium. A mechanical displacement can be made to cause a change of resistance, inductance or capacitance in a circuit element, and hence, a voltage change which can be calibrated against the displacement.

One further reason why vibration testing is of direct interest to the radio engineer is the increasing demand throughout the industry for reliable valves and components, and manufacturers are required to carry out specific vibration tests on their products to be supplied under government contracts.

The need for laboratory equipment to simulate the operating conditions is obvious. The cost of operating an aircraft, tank, or ship for only a few hours, in connection with equipment testing, can be a very costly item. In the aircraft industry a wide range of vibration measurements have been taken on a large number of different types of aircraft, and from these statistics a series of average conditions have been approximated. All prototype electrical and electronic equipment may be required to operate satisfactorily when subjected to these conditions. The need for this type of testing extends to equipment included in all fighting vehicles and, to a lesser degree, motor cars and factory installations, etc.

The large amount of vibration testing which is being carried out to-day in all these applications calls for a very versatile type of equipment. Mechanical vibrating tables are, in general, limited to an upper frequency of a little over 100 c/s. Furthermore, it is not normally possible to alter the amplitude or force without first bringing the system to rest and making some mechanical adjustment. The constant-amplitude type of table is, however, most convenient when calibrating vibration pick-ups. Since this type of table is, of necessity, driven by some form of motor, the frequency stability is not as high as is sometimes required.

An oscillator-controlled vibrating table gives the immediate advantages of wide frequency range and a high degree of stability. In conjunction with a suitable power amplifier, it only remains to provide the best type of transducer to take full advantage of these properties.

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U.D.C. No. 621.389 : 620.17.

2. The Moving-Coil Vibration Generator

A moving iron arrangement offers a simple and cheap design for a vibration generator, but suffers from the disadvantages of low efficiency, distortion, and a comparatively low upper frequency limit due to the mass of the moving iron element. Some early loudspeakers were designed on this principle, but when the moving-coil type was introduced they were soon discontinued.

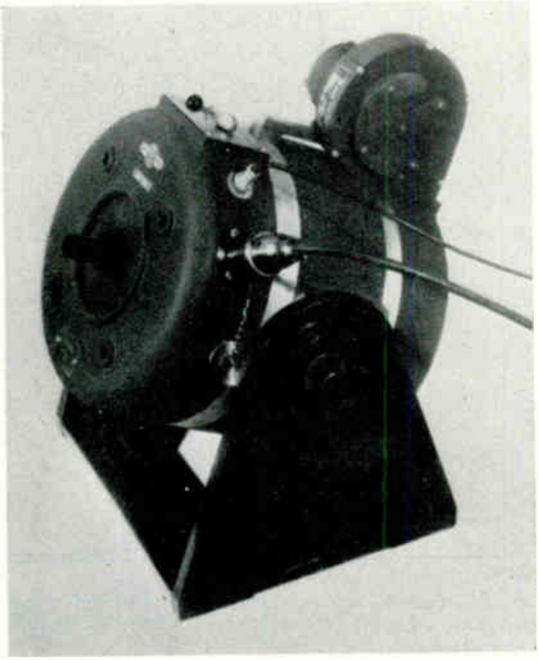

Fig. 1.—A large vibration generator (Goodmans Model 8/600). This is suitable for vibrating heavy components or complete assemblies, and is capable of producing a force of ± 300 lb.

The development of the moving-coil vibration generator has been along the lines of modern loudspeaker practice, mains energized and permanent magnet types being available.

Apart from the omission of the radiating cone, the differences are mainly in size and power rating only. This type of instrument provides a linear transducer and the familiar equation: $F = Bli/10$ dynes, provides the force/current relationship.

Figure 1 shows a large vibration generator. The main magnet assembly is of the centre-pole type and is built of a number of sections of Alcomax III permanent magnets with mild steel yoke and pole pieces. The armature is mounted on a central driving spindle, which, in turn, is mounted on two bakelized fabric suspension spiders. This type of suspension affords a high degree of flexibility in the operating axis and provides a stiff radial location of the armature.

A separate ring magnet assembly provides the operating magnetic field for a pick-up coil which is concentrically mounted on the driving spindle. This pick-up, or monitor coil, generates a voltage output which is proportional to, and in phase with the velocity of the vibration.

A motor-driven air-blower provides cooling air which is driven through the operating gap and therefore permits a somewhat greater power dissipation.

The general limiting factor of this type of instrument is the maximum force it can produce, and for this particular model alternating forces up to ± 300 lb can be produced. The audio-frequency power required to produce this force is of the order of 1 kW.

There is no lower limit to the frequency response of this type of unit and the upper frequency is limited only by the inertia loading of the moving assembly. A practical limit for this particular model is about 3 kc/s. At this frequency the amplitude of vibration obtainable is extremely small (i.e. $<$ ·001 in), but the construction permits a total excursion of 1 in for the lower frequency investigations.

3. Theory of Operation

3.1. *Dynamic Response*

If the unloaded vibrator is driven by a variable frequency current of constant amplitude, the steady-state vibration amplitude will vary as in Fig. 2. The resonance peak indicated at f_0 is determined by the stiffness of the suspension and the mass of the moving parts and is usually below 30 c/s. When vibration tests are being carried out on instruments or components, etc., additional mass loading of the vibrator will cause the resonance peak to be exhibited at a lower frequency. If it is desirable to increase the frequency at which the fundamental resonance occurs, the suspension stiffness can be increased by the introduction of an external diaphragm or spring.

At frequencies well below the natural frequency, the system is said to be stiffness controlled and the steady-state displacement amplitude is independent of frequency. The system is mass controlled at frequencies well above the natural frequency and under these conditions the acceleration is independent of frequency. For a given mass, and with a knowledge of the current flowing in the coil, an estimation of the peak acceleration can be made from the basic equation:

$$\text{Force} = \text{Mass} \times \text{Acceleration}.$$

A constant velocity response is displayed at frequencies near the resonant frequency when the system is resistance controlled, but it is not possible to extend this condition over a very wide range. By a suitable choice of mechanical constants it is possible to place one or another of these ranges in the desired place in the frequency scale. It will be noted that there is always an upper limit to the frequency range over which the dynamic system is stiffness controlled, a lower limit to the range over which it is mass controlled, and both an upper and a lower limit to the range over which it can be resistance controlled. These limits can be moved about by changing the mechanical constants, but the limits cannot be removed entirely.

The peak in the curve of amplitude against frequency is sharp if the damping is small and is broad and low if the damping factor is large (Fig. 2). This figure shows that the steady-state motion of the system is not very sensitive to the value of the frictional constant except in the range of frequencies near resonance. The dotted curve for the amplitude of motion is for a value of damping ten times that for the solid curve, yet the two are practically equal except in this frequency range.

The motion is not usually in phase with the force, the displacement lagging behind the force by the angle β which is zero when $f = 0$, is $\pi/2$ when $f = f_0$ and approaches π as f approaches infinity. The angle of lag of the velocity behind the force, $\theta = \beta - \pi/2$, is analogous to the phase angle in a.c. theory.

Summarizing then, when the frequency of the driving force is much smaller than the natural frequency of the mounting, then the amplitude is small and the displacement is in phase with the force. As f is increased, the amplitude increases and gets more and more out of phase with the force, until at resonance the amplitude is large, and the velocity is in phase with the force. As f is still further increased, the amplitude drops down and eventually becomes very small. For the large values of f the displacement is opposed to the force.

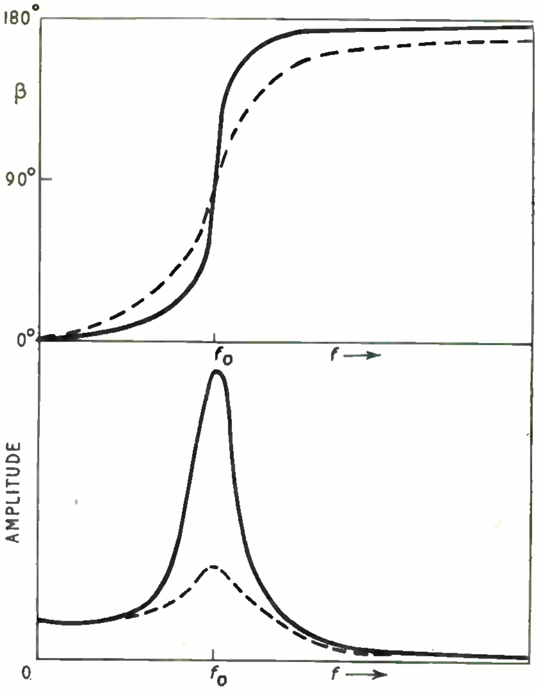

Fig. 2.—Curves showing the amplitude and phase relationships against frequency for a moving-coil vibration generator.

3.2. *Motional Impedance Measurements*

The operation of the electro-dynamic exciter is reversible and whilst an electrical current in the coil will produce a mechanical force, a mechanical movement will produce an electrical voltage.

The mechanical properties of the system to which the armature is attached will, therefore, be reflected into the coil in an electrical form. This has the effect of altering the impedance at the terminals of the coil, and since the change is due to the movement of the coil, the added impedance is called the motional impedance. The two important characteristics on which the measurements are based are:—

(*a*) When the moving coil of the vibrator is

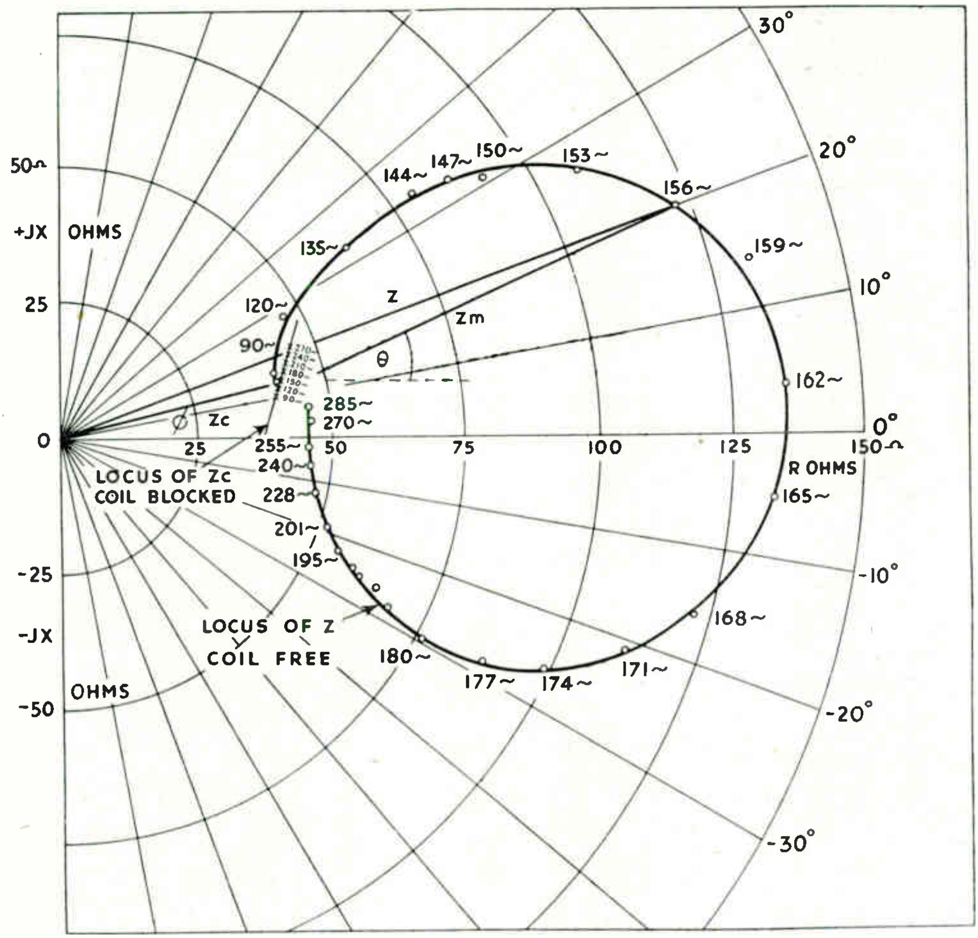

Fig. 3.—Polar co-ordinate plot showing the locus of Z_c and Z.

supplied with a sinusoidal current, a sinusoidal force is exerted which is proportional to and in phase with the current.

(*b*) When the moving coil is caused to move in the magnetic field of the vibrator, a back e.m.f. is generated which is proportional to and in phase with the velocity.

The force developed on the armature is given by the electrical motor equation, $F = Bli/10$ dynes, where B is the flux density in the gap in gauss, l is the effective length of the conductor (moving coil) in centimetres and i is the current in the moving coil in amperes.

The equation for the induced e.m.f. is:— $e = Blv \times 10^{-8}$ volts, where v is the velocity of the coil in cm/sec, and B and l as before. The product is a constant of the vibrator and can now be called K.

It can be seen now that when the coil is being driven, the voltage equation for the coil is:—$E = iZ + e$ where E is the applied voltage in volts, i is the current in amperes, Z is the electrical impedance of the coil and e the back e.m.f. Dividing throughout by i, we get

$$E/i = Z_c + e/i \quad \text{or} \quad Z = Z_c + Z_m,$$

where Z is the terminal impedance and Z_m the apparent added impedance or motional impedance.

To obtain the values of Z_e, the armature should be tightly clamped and measurements of applied voltage, current and phase angle taken at suitable increments, over the desired frequency range.

The locus of (Z_e, ϕ) can then be plotted on a polar chart (Fig. 3). When the armature is subsequently attached to the system under investigation, similar measurements can be repeated. The measured impedance will now be that of $Z_e + Z_m$, so that the locus of (Z, ϕ) may be plotted on the same chart.

The vector difference between two points of equal frequency represents (Z_m, θ) the motional impedance. This vector can be conveniently measured by using a transparent protractor marked with concentric circles to the same scale as the chart. The locus of (Z_m, θ) can now be plotted on a second chart (Fig. 4).

3.3. *Analysis of the Motional Impedance Diagram*

The motional impedance reflected into the coil is directly related to the velocity admittance of the mechanical system. The locus of velocity admittance of a simple system having one degree of freedom is a circle passing through the origin. It can be seen from Fig. 4 that the locus of Z_m approximates to a circle whose main diameter OP is depressed by the angle δ below the real electrical axis. This is due to magnetic hysteresis in the vibrator which causes the magnetic flux, and hence the force, to lag behind the current. The angle δ is a function of the vibrator design and driving current, but in general it is approximately equal to the angle of inclination of the blocked impedance locus to the reactive electrical axis (Fig. 3).

The mechanical phase angle between the force and the velocity will therefore be $(\theta + \delta)$.

The point P indicates the resonance of the system and the frequency can be determined by interpolation.

If the diameter AB is drawn perpendicular to OP the intersections will occur at the frequencies where the velocity is $1/\sqrt{2} \times$ the velocity at resonance, and the phase angle between force and velocity is ± 45 deg. The damping factor can then be calculated from

$$\frac{C}{C_c} = \frac{f_B - f_A}{2f_P}$$

This form of presentation shows immediately the relative variation of velocity together with the phase relationship. By suitable manipulation of the equations and units, expressions can be derived for amplitude, velocity, or mechanical impedance, etc.

The calculated impedances, etc., will apply at the point of input of the force, and for complex modes of vibration it is necessary to take measurements at a number of points on the structure. Various forms of transducers can be used, including the generator-type velocity pick-up.

This is of similar construction to the vibration generator, but is usually wound with a coil of higher voltage sensitivity. Measurements are most conveniently carried out using a c.r.o., and since the displacement amplitude is usually required to be known, an integrating network can be included.

4. Driving Equipment

The choice of driving equipment for a given model will depend largely on the range of frequency to be covered and the degree of stability required over that range. For general purpose audio-frequency testing, an electronic oscillator and power amplifier will respond down to about 50 c/s, and where vibration testing is to be carried out below this frequency special consideration is given to the design of the power output transformer to extend the range down to, say, 10 c/s or lower. Direct-coupled power amplifiers have been used for ultra-low frequency investigations, but so far have not been widely adopted. Some forms of non-resonant fatigue test which can be carried out at a fixed frequency can be driven from the 50-c/s supply mains or from a motor-alternator set arranged to deliver the desired frequency.

Speed-controlled motor-alternator sets are also used for high-power variable frequency supplies over a limited frequency range. One chief disadvantage of this method is that the load variations tend to influence the stability and considerable compensation circuits become necessary. The fact that the output voltage normally varies with frequency places a lower practical limit on the useful frequency range.

A particular type of vibration test in the aircraft industry requires a frequency coverage from about 1–50 c/s and with the full power available at the lower frequencies. This has been

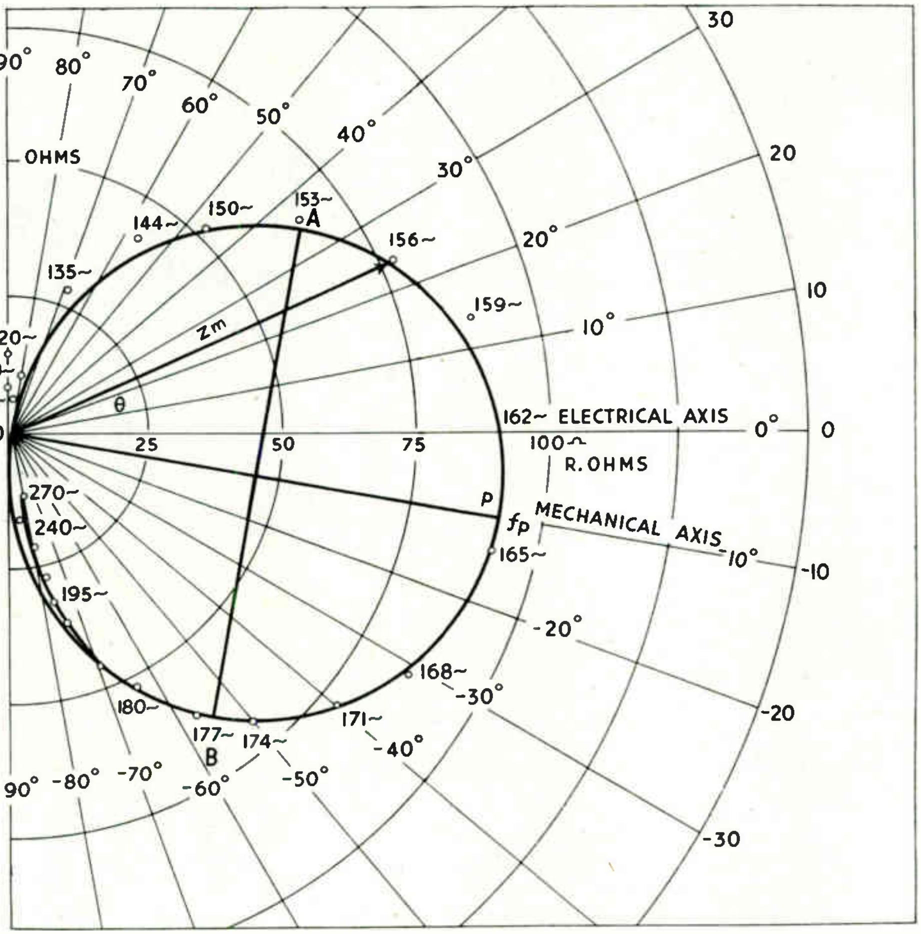

Fig. 4.—Motional impedance diagram.

accomplished by several methods, one of which employs a tapped potentiometer with connections to a stationary commutator. The potentiometer is supplied from a d.c. generator and the rotating brushgear picks off a sinusoidal voltage which is constant throughout the frequency range. The speed control motor which rotates the brushgear need only be of low power, and load variations have little effect on the stability.

With all of the methods discussed, several vibration generators can be driven in synchronism and reversal of the terminal connections of one or more units will provide anti-phase excitation.

When exciting a complex structure at a number of points it may be necessary for the forcing at one point to have a given phase relationship (other than 0 deg. or 180 deg.) with reference to another. Under these circumstances a multi-phase alternator can be used where a suitable combination of the phase windings will give the required phase difference. Alternatively, a continuous variation of phase could be arranged by electronic methods.

By arrangement of series and shunt attenuators, the forcing of each vibrator can be independently controlled in order to promote the desired mode of vibration.

5. Applications

Most applications will fall into two main categories, one covering reliability tests on all types of manufactured goods, and the other investigations of complex structures such as aircraft, bridges and other civil engineering projects. The behaviour of the vibrator in the first case is governed by the type of mounting employed and, in general, it is required to cover a wide frequency range under non-resonant conditions. It is usual to make the natural frequency of the mounting low and work under constant acceleration conditions. This is generally termed "brute force shaking" (Fig. 5).

Radio valves and components are tested in this manner, and among other items are aircraft instruments, motor car accessories, relays, etc. Larger objects like airborne radar scanning units and so forth call for some ingenuity in mounting so as to ensure that the vibration is transmitted into the structure. It is usually necessary to construct some form of frame or cradle and suspend the whole from overhead elastic supports. Functional tests can be carried out while the equipment is being vibrated and any frequency which affects the operation can be noted. The use of stroboscopic lighting will help to determine any mechanical resonances in remote parts of the structure.

For structural investigations it is rather important that the presence of the vibration generator does not unduly influence the dynamic characteristics of the structure. The low mass and stiffness coefficients of the moving-coil vibrator are ideal for this purpose, as opposed to the bulky mechanical exciter of similar force output. In this case, the dynamic response is purely governed by the constants of the structure,

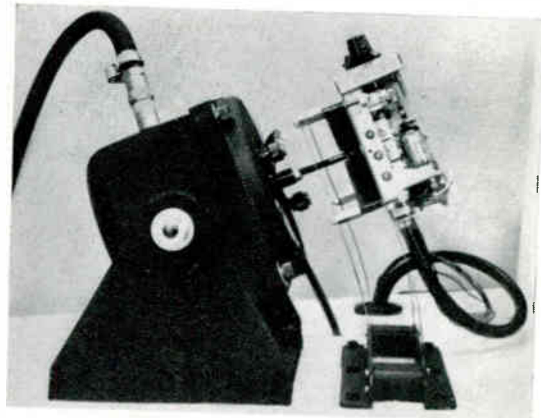

Fig. 5.—Illustrating a method of mounting equipment for vibration tests.

and it is of some interest that electrical measurements on the coil can be interpreted to show some of the mechanical properties.

6. Acknowledgments

The author wishes to thank the Directors of Goodmans Industries, Ltd., for permission to publish this paper and for the facilities provided for the demonstration of equipment at the Symposium.

ELECTRONIC STROBOSCOPES*

by

F. M. Savage†

Read at the Symposium on "Vibration Methods of Testing," December 9th, 1953.

SUMMARY

The principle of operation of the simple type of flash-tube stroboscope is described. The development of a "slow-motion" stroboscope using a phase-shifting potentiometer to maintain a small constant-difference frequency between the frequency of vibration and that of the stroboscopic light source is discussed. Applications of the "slow-motion" stroboscopes to vibration problems are briefly described.

1. Introduction

The principles of stroboscopic observation have been utilized for a very long time and, indeed, certain types of stroboscopes have been manufactured for a great many years.

It was, however, the work done by Professor Edgerton and others in the early 1930's which produced the stroboscopic lamp as we know it, and enabled the electronic stroboscope to be developed. It is this form of stroboscope which is widely used to-day in vibration testing. The earlier stroboscopes were mainly mechanical, and usually consisted of a slotted disc driven by clockwork or a variable-speed electric motor. An eyepiece was fitted behind the shutter and the object viewed through it. As an alternative, a light source was placed behind the shutter which interrupted the beam of light.

These instruments suffered from many disadvantages: a smooth, continuously variable drive was not easy to achieve, the level of illumination at high speeds was low, and when the eyepiece was used the area of viewing was extremely restricted. The electronic stroboscope with its built-in oscillator, on the other hand, is capable of producing extremely short-duration flashes of light, the repetition frequency of which can be easily varied and maintained to very close limits, and can provide a high degree of illumination.

2. Principles of Operation

Figure 1 shows the functional circuit of a typical stroboscope. It consists fundamentally of a stable variable-frequency oscillator, usually a multivibrator, and an electronic flash tube, together with the charge capacitor. The anode and cathode of the flash tube are connected across the capacitor which is charged via a resistor from the h.t. supply. Grid 2 is connected to a positive voltage and the firing or triggering pulse produced by the oscillator is applied to grid 1.

When the potential of grid 1 reaches a critical value, the gas in the gap between the third and fourth electrodes is ionized, thus allowing the capacitor to be discharged through the tube. It will be seen that the intensity of the discharge flash will depend upon the size of the charge capacitor and the voltage to which it is charged. The tube shown in the circuit is of the neon type,

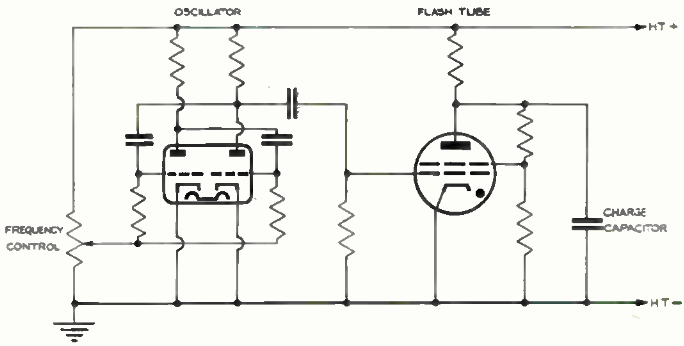

Fig. 1.—Functional circuit of typical stroboscope.

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† Dawe Instruments, Ltd., Ealing, London, W.5.
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operated at about 280–300 V h.t. potential, and is used when only moderate intensity of flash is required.

Other tubes are available, filled usually with Xenon, which may be operated at potentials of several thousands of volts. The trigger electrode is sometimes mounted internally or may consist of a length of wire wrapped around the outside of the glass envelope. Referring to the circuit of Fig. 1, the trigger pulse is shown originating from the oscillator, but with most commercial stroboscopes provision is made so that the flash may be initiated by external means, such as the output from an electro-magnetic pick-up, a photocell, or the closing of a pair of contacts. The stroboscope is widely used for determining the speed of revolving or vibrating objects, particularly when no mechanical loading is permissible, e.g. the speed of a vibrator.

If the rate at which the light source is flashed equals the rate at which the object is revolving, the object will be illuminated in the same position by each flash and will appear to be stationary, the revolution speed being the same as the frequency of the oscillation. The object will, however, also appear to be stationary when the flash rate is a sub-multiple of the revolution speed. The following procedure should be used to prevent errors because of this. The oscillator is adjusted until a stationary image is obtained and the frequency x of the oscillator noted, the frequency is now reduced until a second stationary image is obtained, y. The actual speed is then given by: $\frac{xy}{x-y}$.

Whilst flash tubes are available which can be operated up to several thousands of cycles per second, they are very expensive, and if any great intensity of illumination is desired they usually require forced cooling. However, by using the sub-multiple technique, it is possible to measure speeds of up to 90–100,000 r.p.m., using a flash tube whose maximum flash rate is of the order of 18,000 r.p.m. Under reasonable conditions, it is possible to achieve quite good observations when flashing the tube at only 1/5th of the revolution speed.

In a similar manner, speeds lower than the oscillator frequency can be measured by running the oscillator at twice revolution speed when two images will be seen, at three times—three images, etc. When working at high flash rates, the duration of the flash becomes very important if we are to get an image free from blur. For example, at a speed of 10,000 r.p.m. one degree of movement occupies only 17 microseconds, and if we have a wheel of some 3 in radius this represents a movement of a point on the circumference of about 1/20 in. It will thus be seen that unless the flash duration is kept extremely short, blurring of the image will result. At the lower end of the frequency range persistence of vision falls off very badly below about 500 r.p.m.; this can be partly offset by increasing the intensity of the flash, and by working in complete darkness so that extraneous light does not affect the eye. Under these circumstances it has been possible to observe the action of the shuttle of a loom down to about 100 r.p.m.

3. The "Slow-Motion" Stroboscope

So far we have dealt with the case when the flash rate has been adjusted to give a stationary image. If the rate at which the light source is flashed is slightly smaller or greater than the rate of rotation, the object will appear to move slowly in the same or opposite direction, respectively, to that of the actual motion, and at a rate equal to the difference between the flash frequency and the speed of rotation, thus giving a slow-motion stroboscopic effect.

When individual components or complete assembles are tested for mechanical resonances which may be excited at certain vibration frequencies, it is current practice to mount them on an electro-mechanical vibration generator driven from an oscillator and power amplifier, and to vary the oscillator frequency, and thus the vibration frequency, over the range from 10–500 c/s. At the same time, the component is examined visually with the aid of a stroboscopic light source. However, if the stroboscopic light is synchronized with the vibration frequency, only one part of the vibration cycle can be observed. In order that the magnitude and mode of a resonance may be studied, it is usual to employ a separate oscillator to drive the stroboscopic light source and to vary its frequency to maintain a slight-difference frequency with respect to the vibration generator oscillator. Thus the frequency of both oscillators must be varied simultaneously if a small constant-difference frequency is to be maintained. This adjustment is quite critical and a sweep through the range cannot be carried out.

To overcome these difficulties an instrument known as the "Slow-Motion" Stroboscope* has been developed. In this instrument the signals used to drive the vibration generator and the stroboscope are both derived from the same oscillator, only one calibrated control being necessary. The circuit diagram is shown in Fig. 2.

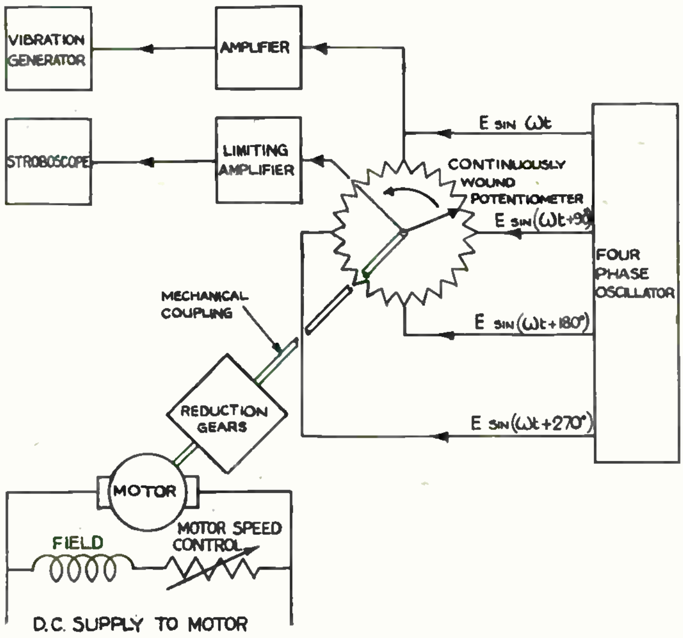

Fig. 2.—Block diagram of the "Slow-Motion" Stroboscope.

The signal for the vibration generator amplifier is obtained directly from this oscillator, but the signal to the stroboscope is continuously shifted in phase at a rate of 360 electrical degrees in a time equal to the period of the required difference frequency. Thus, if the required difference frequency is n cycles per second, the phase is advanced or retarded 360 deg at a rate of n times per second, and the effective output frequency from the phase-shifting device will be equal to the oscillator frequency plus or minus n cycles per second respectively.

The phase-shifting device consists of a continuously-wound resistive potentiometer, the sliding contact of which is rotated by a motor drive. In the circuit four tappings are shown, one every 90 deg of the potentiometer winding. Each tap is supplied with a signal from a four-phase oscillator such that the electrical phase-shift corresponds with the physical angular displacement of the tap.

For example, if one tap is fed with a sinusoidal signal represented by $E \sin \omega t$, where E is the maximum amplitude and ω the angular frequency, the next tap displaced 90° in a clockwise direction is fed with a signal $E \sin (\omega t + 90°)$; the tap at 180° is fed with a signal $E \sin (\omega t + 180°)$ and the tap at 270° with a signal $E \sin (\omega t + 270°)$.

The continuous phase-shift can be achieved with a potentiometer having any number of taps from three upwards by using an oscillator having a corresponding number of output phases. If the sliding contact of the potentiometer is driven in an anti-clockwise direction as shown, the output frequency from the phase-shift is equal to the oscillator frequency minus the speed of rotation of the motor driving the sliding contact. If the sliding arm is driven in a clockwise direction the sum instead of the difference of the frequencies is obtained.

The position is, of course, reversed if the sequence of advancing phases from the oscillator is taken in an anti-clockwise, instead of a clockwise direction, for example, by reversing the supply connections to one pair of opposite taps. It will be seen that the difference frequency is determined by, and is, in fact, equal to, the rate of rotation of the sliding contact of the potentiometer, and it can thus be conveniently controlled by varying the motor speed. Since the object of this instrument is to provide slow-motion observation, the motor is geared down to give a maximum frequency difference of two cycles per second. As can be seen from the circuit, the signal for the vibration generator amplifier is taken from one fixed phase of the oscillator whilst the signal for the stroboscope is taken from the slider of the phase-shifting potentiometer through a limiting amplifier. This limiting amplifier reduces the variations in the signal level which result from using a phase-shift with a relatively small number of tapping points.

* British Patent Application No. 14630/52.

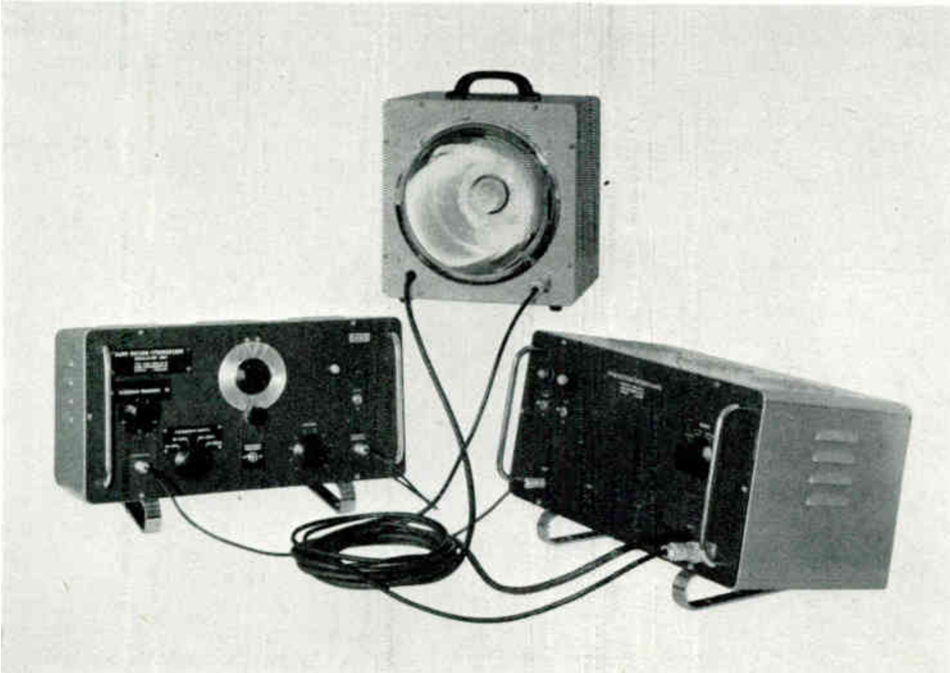

Fig. 3.—"Slow-Motion" Stroboscope as used in resonance search tests. The unit on the left contains the oscillator and motor-driven phase-shift potentiometer; the unit on the right is the power supply.

4. Applications of the Stroboscope

Some vibration problems which have been solved by stroboscopic means will now be described.

(1) The first case was a form of stitching machine in which a curved needle travelled backwards and forwards in a wide arc; during part of its travel the point of the needle passed along a grooved steel plate. The speed of operation was approximately 1,000 r.p.m.

Fundamentally, there was nothing to prevent the machine being run at a considerably higher speed, and in the interest of increased production it was decided to do this. However, when the speed was raised it was found that the needle point was always broken off, and examination of the steel plate showed that the needle was striking the plate at the point of entry to the groove.

The plate was removed so that the machine could be run at the required speed without fracturing the needle, and the operation carefully observed with a stroboscope. It was noticed that, at a speed slightly under the maximum, the needle point vibrated with considerable amplitude due to resonance. The amplitude was greater than the width of the groove, thus causing the needle point to be fractured by striking the end of the plate instead of entering the groove. The needle was re-designed to put its resonance frequency outside the operating speed range and these machines are now run satisfactorily at the increased speed.

(2) The second case concerned a crank-shaft grinding machine, the fault being that "flats" were being produced on the shaft. This fault was extremely puzzling since some twenty machines had been built without trouble. Basically, the machine consisted of a heavy grinding wheel mounted on a beam made of H-section material and driven by an electric motor.

The wheel revolved against the work piece which, in turn, was driven by a separate electric motor. Before investigations were started the two motors and the grinding wheel were exchanged for units known to be free from excessive dynamic unbalance.

It was found possible to adjust the machine so that only the flat was being ground, and by adjusting the flash of the stroboscope to coincide with the sparks produced by contact of the grinding wheel with the shaft, it was possible to determine the frequency at which these flats were being produced. The next stage was to measure by means of the stroboscope, the speeds of the two electric motors which were of different types and running speeds. The speeds were found to conform to the makers' rating, but it was observed that the speed of motor A minus the speed of motor B equalled the frequency at which the flats were being produced, in other words the beat frequency of the two motor speeds.

A simple mechanical vibrometer was obtained and fastened to the beam carrying the grinding wheel. The vibrometer was then adjusted to give maximum amplitude of vibration, and the frequency measured by means of the stroboscope. This figure was found to be the same as the beat frequency of the two motors and also the frequency at which the flats were being produced.

At this stage it appeared fairly certain that the resonance frequency of the beam was actually the same as the beat frequency of the two motors. To prove this, a section was carved out of the beam and vibrations ceased. A careful check was then made, and it was discovered that the beam in question, although dimensionally the same as those on the first twenty machines, had, in fact, been made from material of slightly different thickness.

Throughout the investigation the only instrument used was a stroboscope since the vibrometer cannot really be classed as an instrument. The use of a vibration meter and analyser would probably have helped considerably, but time was the important factor and these instruments were not to hand.

(3) The "Slow-Motion" stroboscope described above is essentially an instrument for the examination of the behaviour of components, etc., which are being deliberately excited. A rather different method of testing which, since utilizing a stroboscope device, may be of some interest.

An armature or rotor can be in perfect balance statically when checked on knife edges, but may show considerable dynamic unbalance when revolving. If such a rotor is built into a machine, excessive vibration and wear on the bearings will almost certainly result. Since this dynamic unbalance can only be detected when the body is revolving the following method of testing is sometimes adopted.

The rotor under test is supported on flexibly mounted bearings, which are free to move in one plane only, and are mechanically coupled to electro-magnetic pick-ups. When the body is revolved, any dynamic unbalance present will cause the bearings to vibrate at an amplitude proportional to the unbalance; for a given angular speed, the e.m.f. induced in the pick-up coils will be directly proportional to the amount of unbalance. This e.m.f., after amplification, is fed into a suitably calibrated meter and the amount of unbalance directly indicated. In addition, the signal after further amplification is differentiated and the negative pulse used to fire a stroboscopic lamp. If the rotor has been suitably marked, e.g. with numbered tape, the angular position of dynamic unbalance will be clearly indicated by the stroboscopic light. It is at this position that correction must be made to restore balance.

5. Acknowledgments

The author wishes to express his thanks to Dawe Instruments Ltd. for permission to present this paper.

RESISTANCE STRAIN GAUGES AND VIBRATION MEASUREMENT*

by

P. Jackson†

Read at the Symposium on "Vibration Methods of Testing," December 9th, 1953.

SUMMARY

Wire and foil strain gauges are described and their properties as transducers discussed. The limitations are also considered. Recording systems for strain gauge work are described which use direct recording, and d.c., carrier and pulse amplification techniques respectively.

1. Introduction

It is proposed to treat the strain gauge as an electro-mechanical transducer, and we shall concern ourselves with the means of using the electrical information supplied by the strain gauge to provide useful data for the engineer. The means are almost entirely electronic in so far as vibration studies are concerned.

2. Wire and Foil Strain Gauges

As a transducer, the strain gauge is of the resistive type. The electrical energy is supplied to it and the physical effect modulates this energy.

The resistance strain gauge (Fig. 1) is perhaps the simplest transducer used in the art. The wire gauge consists essentially of a grid or helix winding of fine resistance wire of 0·001 in. diameter or less, wound on to paper backings, bonded into a matrix of cellulose acetate cement and protected by further layers of paper. The ends of the winding filaments are spot welded or soldered to lead-out tags or ribbons.

The foil gauge, shown in Fig. 2, consists of an epoxy-ethylene lacquer backing bonded to foil which is printed and etched to the desired configuration. It has advantages over the wire gauge of which the most important in this discussion of vibration measurement is its greatly increased power sensitivity.

In use, the gauge is cemented to the specimen under test, and is then considered to be integral with the specimen surface. Any strains in the specimen will be proportionally reproduced in the strain gauge winding, thus producing linearly related increments or decrements of resistance according to the sense of the applied strain. Fig. 3 shows an installed foil gauge.

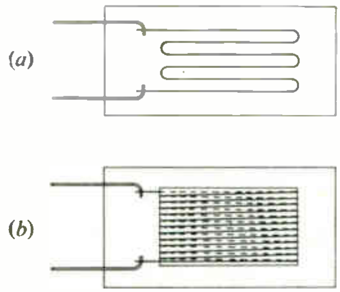

Fig. 1.—Grid and helix wire strain gauges
(a) Flat grid
(b) Flattened spiral grid.

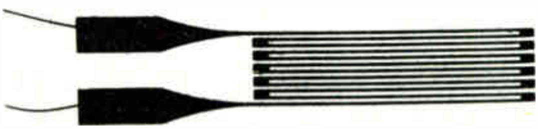

Fig. 2.—Foil strain gauge.

For normal gauges the relationship between strain and resistance is expressed by:—

$$\frac{\Delta R}{R} = Ke$$

where $\frac{\Delta R}{R}$ is the fractional change in resistance.

e is the strain, or fractional change in length

K is a constant known as the gauge factor.

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U.D.C. No. 621.389 : 620.17.

This expression may be rewritten:—

$$\frac{\Delta R}{R} = (A + B)\frac{\Delta L}{L}$$

where A is related to Poisson's ratio, and B relates to the inherent strain/resistance properties of the alloy.

The effect of B is to raise the theoretical gauge factor due to A only from about 1·6 to 2 to 2·3. It is thought that the value of the B term reflects the metallurgical history of the material, and also that consistent values are shown only by cold-worked materials, e.g. drawn wires or rolled foils.

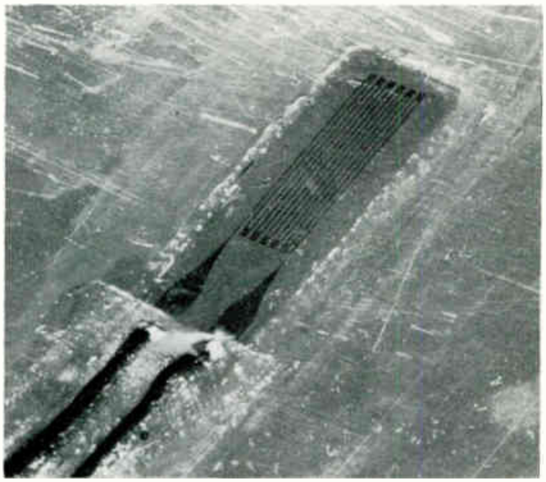

Fig. 3.—Installed foil strain gauge.

It is important to realize that an installed strain gauge is constituted by these three elements:

(1) The strain-sensitive resistance element,

(2) The paper/cellulose acetate matrix or other backing,

(3) The cement layer between the gauge and specimen.

It has these advantages: its operating frequency range is from zero frequency to about 100 kc/s; its size and weight are negligible, it has a wide range of working temperatures, and it is easy to apply. It is, however, relatively insensitive and it is not specially robust. Developments of the foil gauge have largely overcome these two latter disadvantages.

As regards frequency range the vibration engineer is rarely interested in frequencies exceeding 5 kc/s, and in general practice a very much lower upper limit is acceptable. Specialized gas turbine applications may require a bandwidth of up to 30 kc/s, but this is probably a unique requirement. Electronically speaking, therefore, we are in the very low-frequency region.

As regards temperature range, this depends almost entirely on gauge construction and the bonding adhesive and may be between −20°C or less up to 1,000°C or more.

The electronics engineer is always interested in the electrical output of a transducer. The output of the normal wire and paper gauge is limited by its maximum permissible dissipation which is a fraction of a watt, and where long-term stability is of interest may be very small. For the foil gauge it may be several watts. The output is also proportional to the gauge factor but K does not often greatly exceed 2·0.

In practice, the output voltage range is generally from 2 mV to possibly 100 mV, though this latter figure would generally represent mechanical conditions close to failure, or a very high polarizing voltage. Experience shows that the general range of interest is from 2 mV to 50 mV.*

3. Principles of Measurement

Having examined the frequency and sensitivity limitations of the transducer we now pass on to the means of displaying or recording the desired information.

Figure 3 is the simplest possible arrangement; since we know the input to the oscilloscope will be of the order of millivolts, the required gain is deduced from the Y deflection sensitivity of the c.r.t. One would require typically a gain of 10,000 times to 15,000 times. The time base frequency is defined by the mechanical vibration frequency, and should be capable of linear display of at least two complete cycles.

The Y-axis amplifier bandwidth should be sufficient to reproduce the waveform with no appreciable phase distortion. The accurate

* Further information on foil strain gauges is given in the following: P. Jackson, "The foil strain gauge", *Instrument Practice*, 7, August 1953, pp. 775-786; P. Eisler, "Printed circuits: some general principles and applications of the foil technique", *J.Brit.I.R.E.*, 13, November 1953, p. 532, also "Discussion", pp. 539-540.

presentation of phase relationships is important and this requirement does make general-purpose strain gauge amplifier design difficult, since the phase shift or the sum of $\tan^{-1} 1/\omega CR$ for the amplifying stages tends to increase as the frequency is reduced.

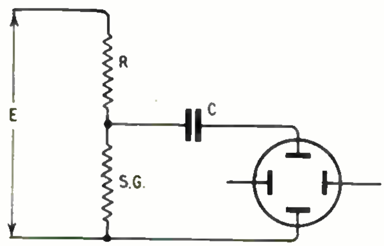

Fig. 4.—Basic diagram of a dynamic display arrangement.

Clearly, in this circuit, E the polarizing voltage, and R the series resistance of the potentiometer configuration must be as high as possible to obtain good sensitivity. C, the input blocking capacitor, must be chosen in conjunction with the input stage grid resistor to avoid low-frequency attenuation and the overall time constant should be at least ten times the lowest signal frequency, otherwise distortion of the input waveform due to time differentiation of the low-frequency components will certainly occur.

If a recording is required then it may be done by mounting a moving film camera to photograph the c.r.t. With a reasonably steady signal the time base swept display may be photographed as a "still" though this would be unusual. It is more normal to switch off the time base and move the film past the c.r.t. face.

This simple system can be extended to cover a few separate bridges by switching the input at high speed by a motor-driven switch and here there is necessarily a severe limit on the upper frequency. Fig. 5 shows the arrangement of a typical multi-point recording scheme, which incorporates temperature compensating gauges.

This example was chosen to illustrate a simple and practical means of displaying strain gauge signals. It is not recommended for any purpose other than, say, visual assessment of dynamic conditions and, without the most stringent precautions, the results would be inaccurate and difficult to interpret quantitatively. The method has been described as an introductory step to more elegant and accurate methods.

4. Practical Display Methods

The frequency spectra of the mechanical requirements may be placed into three categories as follows:—

0 — 150 c/s

2 or 3 — 1,000 c/s

20 — 50,000 c/s and above

and each of these categories define the requirements of the associated electronic and recording equipment.

These divisions of the mechanical frequency spectrum and the necessary equipment are also related to the means used to energize the gauge, which may be:

(1) d.c. energization, used from zero frequency to upper limit

(2) a.c. energization, used from zero frequency to about 1/5 of a.c. frequency

(3) pulse energization, used from zero frequency to about 1/5 of p.r.f.

It is proposed to describe briefly systems based on these categories.

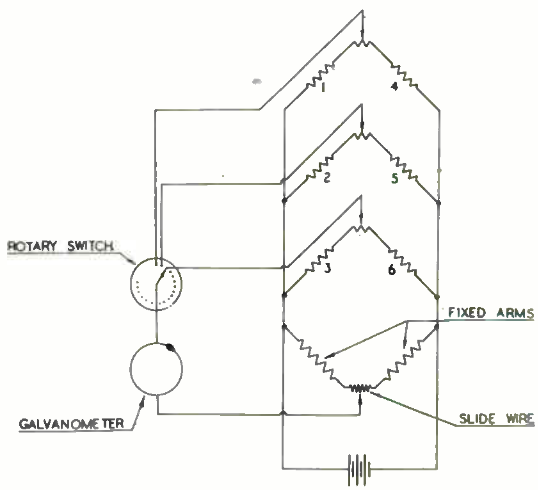

Fig. 5.—Multi-point recording scheme: 1, 2 and 3 are active gauges; 4, 5 and 6 are temperature compensating gauges.

4.1. *Direct Recording*

A simple system is based on the foil strain gauge and a compact 12-channel galvanometer recorder designed by the Admiralty Research Laboratories. One of the most important advantages of the foil strain gauge is its very high dissipation capabilities which may be exploited in dynamic stress investigations, and by applying a sufficiently large power input it is possible to drive a high-frequency recording galvanometer to well over 100 c/s.

The overall sensitivity of the system is controlled merely by the applied voltage, which must be held constant or alternatively monitored during the experiment. As the system is operating at low impedance levels (50–60 ohms) there should be no difficulty caused by hum pick-up, though it might be advisable to check this in the case of very long lines in strong fields. A last point is that the system is unique in that the gauges are power-sensitive; all other systems are based on voltage sensitivity.

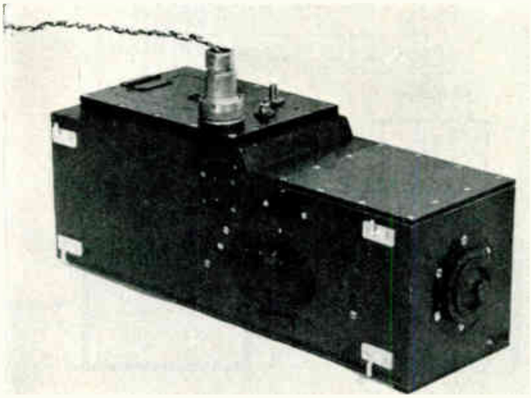

Fig. 6.—A.R.L. 12-channel galvo recorder.

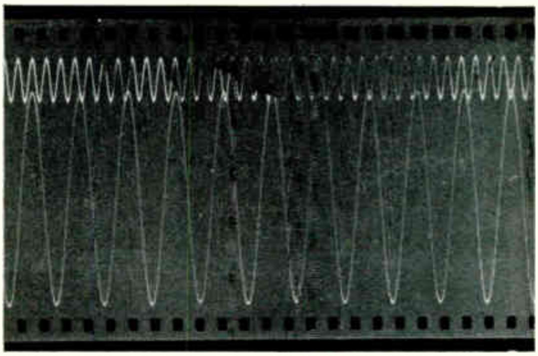

Fig. 7.—Typical record from A.R.L. recorder.

The A.R.L. recorder shown in Fig. 6 is based on 12 galvanometer elements sharing a common magnet block. It has a particularly neat optical system and the recording is made on 70-mm film. With external resistive damping the present upper frequency limit of the galvanometer is 150-180 c/s, so that this simple instrumentation will adequately satisfy any requirements in the first section of the mechanical frequency spectrum. The system has the merits of simplicity and elegance and it serves to cover the majority of structural and mechanical researches.

Figure 7 illustrates a typical recording taken on this equipment.

Before passing on to the next system, there are one or two points to be made regarding the direct-driving technique. Since fairly high-power inputs to the gauge are required, temperature compensation becomes important, and whenever possible a fully active four-arm bridge should be used. This also obviously assists in sensitivity.

4.2. *D.C. Energization and Amplification*

The Savage & Parsons 6-channel dynamic recording equipment (Fig. 8) is one of the very few commercially available systems based on d.c. amplification of the strain gauge signal. The complete equipment very adequately covers the second portion of the frequency spectrum by using alternatively a Duddell-type galvanometer camera or a cathode-ray tube camera. With the former camera, the upper frequency limit is 1,000 c/s; with the latter, 4,000 c/s limit is imposed by the maximum speed of the film transport mechanism which is 50 in/sec. In the present author's opinion, the 4,000-c/s figure quoted against this specification is beyond the useful limit of legibility on a film recording, certainly for a reasonably sinusoidal signal input.

The noise level is stated to be equivalent to 0·1 mV at the input, and the maximum drift does not exceed ± 1 mV per hour. This last figure illustrates the main disadvantage of d.c. amplifier systems. A total drift of 2 mV in an hour can be a serious matter in certain recording work.

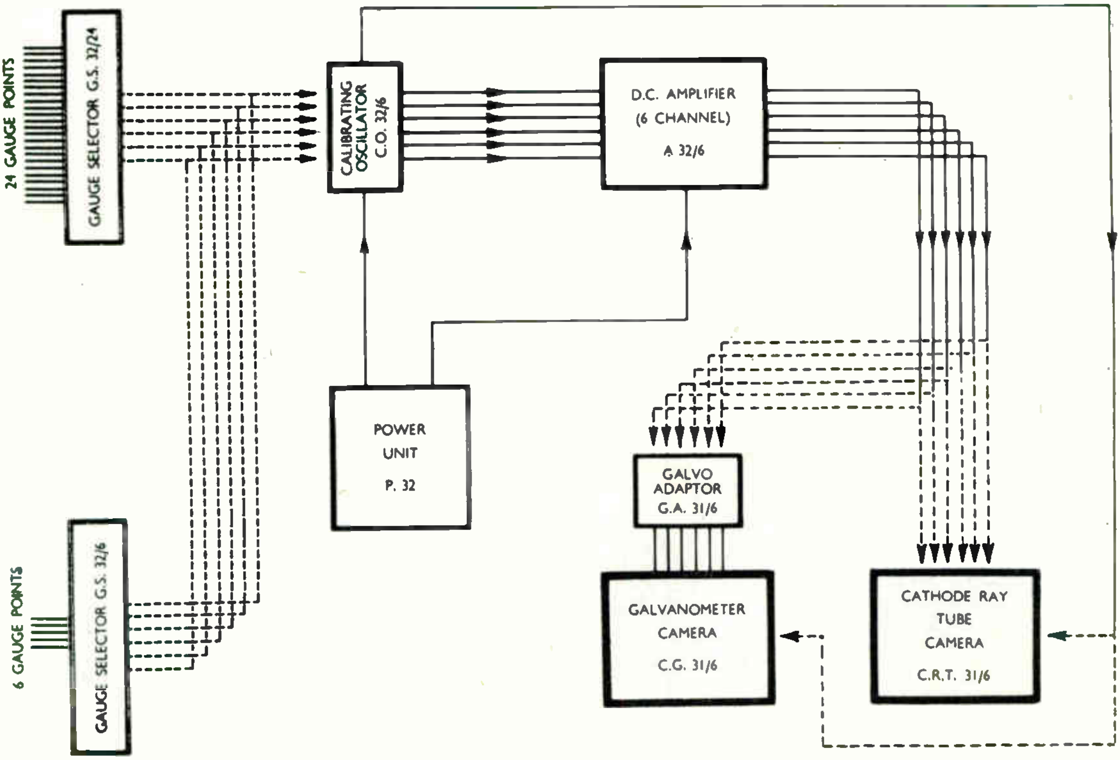

Fig. 8—Schematic diagram of Savage & Parsons 6-channel recording equipment.

For instance, it might be necessary to investigate vibration fatigue frequencies against changes in static loading which might not themselves produce a 2 mV signal. In addition, one often has to accept a wandering base line on the record because of drift, and in a simultaneous recording of six traces this is most undesirable. In short-term work, however, drift is of little consequence and the system using gauge energizing and d.c. amplification generally yields simpler equipment.

4.3. *A.C. Energization or Carrier Technique*

At the present stage of development of the art, the carrier technique is enjoying considerable popularity. The frequency range of the system is from zero up to roughly 1/5th of the strain gauge energizing frequency; as this has been set generally at 2,000 c/s, the working range adequately covers the first section of the frequency spectrum.

The main advantage of the carrier technique is that the amplifier requirement is much simplified since it only requires a bandwidth sufficient to accommodate carrier plus sidebands. Since the amplifier is a.c.-coupled there is no zero drift problem and largely for the same reasons the sensitivity can be increased without difficulty.

The major disadvantage in this system was, in the early days, the difficulty of balancing the reactive components of a strain gauge installation. Resistive balance is simple, of course, but the associated wiring can produce astonishingly high reactive unbalance. Also in a simple carrier-demodulator system there is no way of determining the sense of any modulating signal with respect to zero.

These difficulties have been overcome almost entirely by demodulating in a phase-sensitive rectifier. The principle is that the modulated carrier is added to a fixed carrier amplitude and rectified. The two are in phase for a bridge unbalance in one direction and out of phase for the other direction, so that the demodulated output voltage is correctly sensed with respect

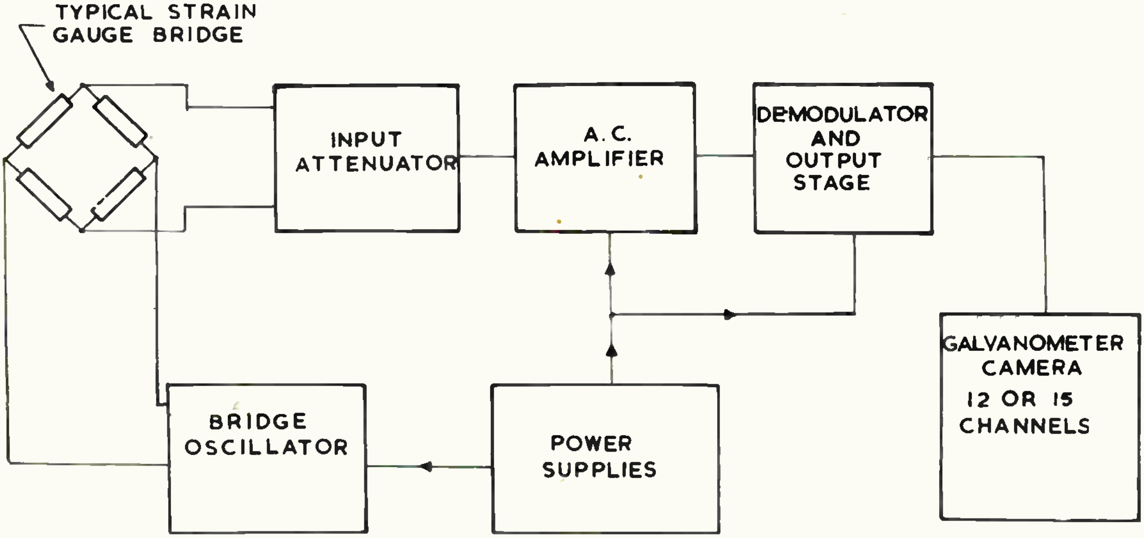

Fig. 9.—Schematic of typical a.c. energizing system.

to zero. The fixed carrier is the phase reference signal, and is easily controlled to cancel initial bridge output voltages due to reactive unbalance of the installation.

The first successful commercial equipment to use the carrier amplifier and phase-sensitive rectifier technique was manufactured by the Miller Corporation of America, and a block diagram of this type of equipment is shown in Fig. 9. It uses a carrier frequency of 2,000 c/s, and the upper frequency limit of recording is therefore 400 c/s. Each amplifier is extremely simple and consists of an input matching transformer to a single-ended triode stage, RC-coupled to a pentode stage followed by the phase-sensitive rectifier. The rectifier output is fed to a cathode follower output stage via a simple double-section filter which removes the carrier frequency. The output stage drives the recording galvanometer.

The recording camera contains a common magnet block with plug-in galvanometer elements which are made in various frequency ranges and sensitivities. The optical system is ingenious and has a provision for inspecting the wave forms during the "take." This is achieved by using a 24-sided revolving mirror which reflects part of the light reflected from the galvanometer mirrors on to a ground screen. The time trace marker is also projected on to the screen and the speed of the revolving mirror is adjustable to provide synchronism.

The time traces are derived from an illuminated slotted disc driven by a synchronous motor, the speed of which is controlled by a vibrator. This provides a line across the record corresponding to 0·01 sec intervals.

In the later models of the equipment, the film width is 6 in., and a gearbox on the film transport mechanism provides recording speeds of 2, 5, 15 and 35 in/sec.

This equipment provides an excellent and versatile means of recording strain gauge data for general structural work. It is not usually expected to record much above 70-100 c/s, which is quite adequate for its designed task of general flight recording.

The second example of the carrier technique is much more modern, and may be the precursor of a new line of development in the art generally. This is the 4-channel dynamic strain recording equipment which was developed by Kelvin & Hughes, Ltd., in conjunction with the Royal Aircraft Establishment.

The major difference between this and the Miller equipment, apart from the number of channels available, is the recording means. The four channels record separately by moving pens on Teledeltos dry recording paper. The pens carry high-voltage probes which burn a very fine trace on the sensitized paper by sparking. Clearly, this facility is an outstandingly useful feature economically and practically. The record is immediately visible and there are no processing costs or delays.

Electronically, this equipment is almost exactly the same in principle as that just described. The energizing frequency is 2,000 c/s, and each amplifying channel consists of carrier voltage amplifying stages, phase-discriminating demodulators and output stage. The design generally is such that strain gauges of from 50 ohms to 20,000 ohms resistance may be used.

Arrangements are also made in the energizing output and amplifier inputs to permit the use of fully active four-gauge bridges.

The overall sensitivity is such that full-scale pen deflection from a pair of gauges, one active and one thermal compensating, is obtained for a 0·006 per cent. resistive change. Converting for a gauge factor of 2, this represents a strain of 30 micro-inches per inch, which corresponds roughly to 900 lb/sq. in. in steel or 300 lb/sq. in. in light alloy (63 kg/cm^2 or 21 kg/cm^2 respectively).

The maximum deflection on the recording pen is $\pm$ 7·5 mm from a centre zero, or 15 mm with a side zero displacement. The paper used is 3 in. wide so that with four pens operating from a common centre line across the paper, the figures quoted represent a reasonably efficient use of the available recording field.

Perhaps the only drawback of this method of recording is that trace overlap cannot be permitted to occur, because of the danger to the recording pens of mechanical interference. Trace overlap is not a practice to be encouraged but it can be an extremely useful safety factor, where the amplitudes may have been underestimated in one or two channels.

Timing data are provided by two fixed pens placed at opposite edges of the Teledeltos paper. They are pulsed at 40 c/s from an internal oscillator and provide a row of dots down each edge of the paper. A further very useful feature is the provision of another fixed pen on the centre line of the paper. This may be used as an event marker, and is then under external control.

Calibration is carried out on the record by switching a known resistance into one leg of the bridge and the makers have provided a sensibly chosen range of resistors for this purpose.

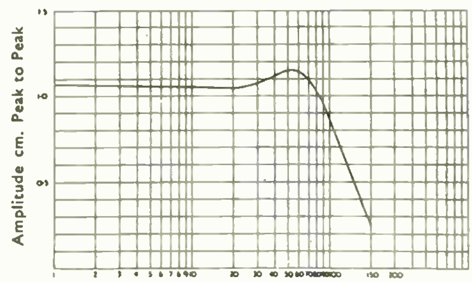

Fig. 10.—Typical frequency characteristics of Kelvin and Hughes 4-channel dynamic strain recording equipment.

The frequency response of the system is from 0–80 c/s and the upper limit is set purely by mechanical considerations of the pen weight, suspension and damping. The response curve is typical of an electro-mechanical system of this nature and is shown in Fig. 10.

The equipment as a whole is compact, reasonably light, robust and engineered to a very high standard.

4.4. *Pulse Techniques*

There is only one commercially available example of pulse energization of strain gauges. It is an excellent and versatile instrument, designed and made by Elliott Bros., Ltd., and comprises a 10-channel display system having a maximum sensitivity of 1-mm deflection for 0·001 per cent. strain.* Fig. 11 shows the block diagram.

The difficulties of switching gauge outputs to a common indicator are overcome by using the confluent transmission principle. This is based

* J. G. Yates, D. H. Lucas and D. L. Johnson, "Multi-channel measurement of physical effects by confluent pulse technique with particular reference to the analysis of strain." *Proc. Instn Elect. Engrs*, **98**, Part II, April, 1951, pp. 109-124.

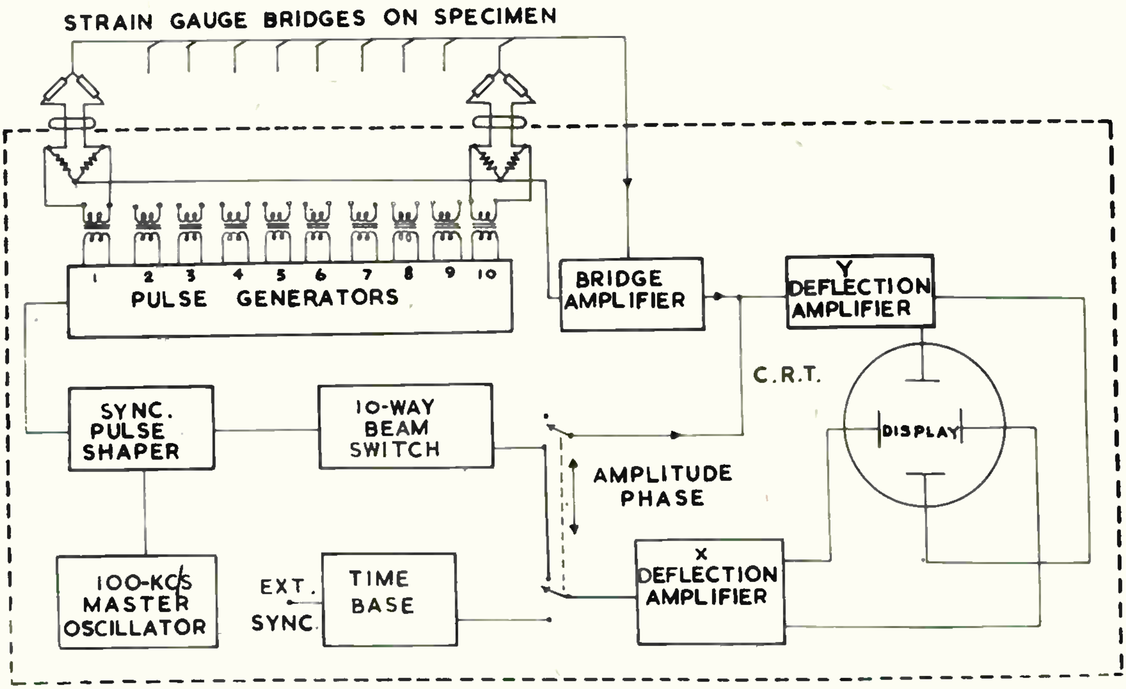

Fig. 11.—Elliott Bros. 10-channel display equipment.

on the rapid sequential sampling of the data and transmitting the information along a common channel. It is thus an example of pulse communication and information is conveyed by the variation of the pulse amplitude.

Significant advantages accrue from the method of switching the energizing input to the gauges rather than the output signals as follows:

(1) The switching of a low-level signal is avoided and, instead, a high-level pulse is switched or distributed sequentially to the gauges. The difference in voltage levels is about a thousand to one, which reduces difficulties due to noise and drift.

(2) The energization pulses are short, and at any instant only one is present in the system. The switching circuits are not required to reject signals from other channels, and no noise is received from gauges other than those being energized. The pulse technique has two further distinct advantages for multi-channel work.

(3) Because of a short duty cycle of 1/10 (energized/idle time) the sensitivity may be increased by $\sqrt{10}$.

(4) The design of the circuitry is such that the effect of unbalanced reactive components in the strain gauge bridges and the associated connecting wires are made negligible.

Consider a resistive bridge with associated stray capacitances across the arms. If a short-duration rectangular pulse is applied and the bridge is resistively unbalanced due to strain, the output will be of the form shown in Fig. 12, that is to say, partial differentiation has occurred, and the reactive component is separated from the resistive component in time. The plateau is a measure of the resistive unbalance and the initial and trailing spikes denote reactive unbalance.

If this output is amplified in the usual manner and applied to a c.r.t., then complete separation of the plateau, and hence measurement of the resistive unbalance, may be made by pulsing the c.r.t. modulator grid to brighten only on a small portion of the plateau.

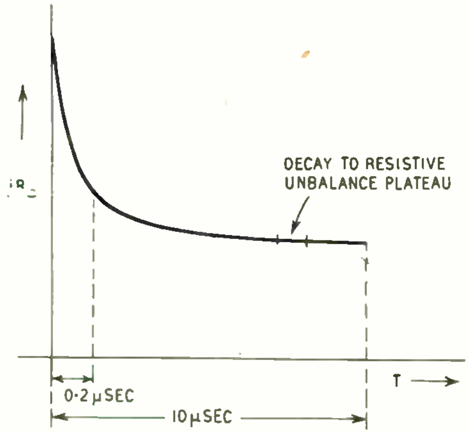

Fig. 12.—Separation of resistive component from the reactive in a strain gauge bridge.

The time constant of the exponential decay down to the plateau or resistive unbalance level is very small—in practice, taking 200-ohm gauge circuits and 100 ft of connecting wire as a typical case, it has been estimated as 0·2 micro-second. Also because of the properties of the exponential function, even if the initial spike is very large, it will be of negligible magnitude after an interval of ten times its decay constant. It can be neglected within 2 microseconds of the commencement of the energizing pulse.

It was found necessary to run the pulse generators as a ring of eleven, so that the gauges are energized at 9·1 kc/s. The interval at the 11th flip-flop is used for flyback and a marking interval. Accurate running is assured by setting the ring to run slightly underspeed and injecting a very short synchronizing pulse into the common cathode line every 10 μsec. Thus the pulse is terminated a few microseconds before its free run-down time and the pulsing rate is thereby accelerated and held to correct frequency.

The equipment is reasonably compact and has been designed for portable use or standard rack mounting; it weighs approximately 60 lb. It is a useful and adaptable type of instrument for general-purpose strain gauge work.

5. Acknowledgments

Thanks are due to the Directors of Saunders-Roe, Ltd., for permission to present this paper.

ELECTRONIC AIDS TO VIBRATION MEASUREMENT*

by

R. K. Vinycomb, B.Sc.†

Read at the Symposium on "Vibration Methods of Testing," December 9th, 1953.

SUMMARY

Transducers for vibration measurement are described, including the variable-inductance proximity pickup, and seismic units of the electromagnetic, variable-inductance, variable-resistance, variable-capacitance, and piezo-electric types. Problems of pre-circuits for the various transducers are discussed. The amplifiers and recorders are dealt with in relation to the requirements for visual presentation and multi-channel recording.

1. Introduction

The measurement of vibration has become a necessity in the design of so many products today that it is not surprising that electronic devices have been called upon to assist. The object of this paper is to show some of the advantages of electronic methods and to describe the principles involved. It is hoped that the examples quoted will illustrate the versatility of electronic vibration-measuring equipment.

In this paper the term "vibration" is treated as meaning "a cyclic displacement of one part relative to another". This excludes transient conditions and "shock". The latter can often, of course, be measured by electronic means but the theory and practical methods may be rather different. Provided that the vibration is cyclic, therefore, it must comprise the sum of a number of Fourier components, each of sinusoidal form, which are combined to form a complex waveform. It may be measured by defining the displacement, velocity or acceleration of the vibrating part with respect to time.

Figure 1 illustrates schematically a vibrational displacement between two parts and gives the mathematical expressions for the displacement, velocity and acceleration of a vibratory motion having a frequency of $\omega/2\pi$. From this it will be seen that the peak values of each differ numerically by factors ω or ω^2. Therefore, if an electrical signal can be produced which is proportional to any one of three parameters, signals proportional to the other two may be obtained by means of integrating or differentiating circuits. Such circuits are those in which the output is attenuated in proportion, or in inverse proportion, to the frequency. The simplest forms of circuits for this purpose consist of a resistance and capacitance, as shown in the figure.

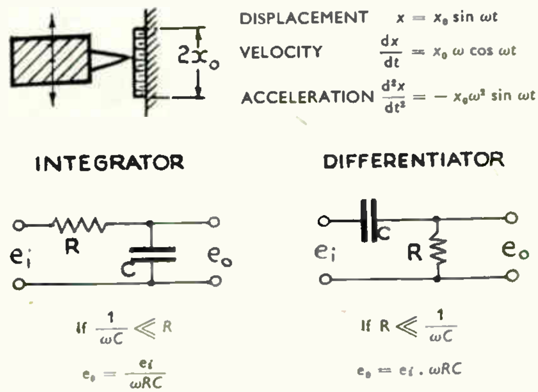

Fig. 1.—The upper diagram illustrates the relationships between vibrational displacement, velocity and acceleration. Below are shown simple circuits for electrically integrating and differentiating a sinusoidal signal.

In order to produce the electrical signal and to present it finally in visual form, a complete recording equipment is required. This may conveniently be divided into four sections as follows:—

(1) Transducer: converting mechanical movement to any convenient electrical quantity.

(2) Pre-circuit: converting any electrical quantity to voltage.

(3) Amplifier: converting voltage to higher voltage or power.

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† Southern Instruments, Ltd., Camberley, Surrey.

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(4) Recorder: converting voltage or power to meter reading or waveform.

The design of transducers is possibly the aspect least familiar to electronics engineers and will be described more fully than the other sections.

2. Transducers

All transducers basically depend on the measurement of a mechanical displacement between two parts. Some examples are:—

(1) Change of capacitance with dielectric spacing.

(2) Change of inductance with change of air gap in the magnetic circuit.

(3) Change of resistance with length of conductor.

(4) Generation of e.m.f. with movement of a conductor in a magnetic field.

(5) Generation of e.m.f. by strain of a piezo-electric material.

The ways in which these effects, and others, can be used are limitless. Some of the more usual methods will be described.

2.1. *Proximity Pickups*

A "gap-measuring" device may be used directly to measure the vibration of some part of a structure if a rigid fixture is available from which the measurements can be made. A device of this kind is usually known as a "proximity pickup" since the output of a measuring head is made to vary in accordance with its proximity to the vibrating part.

A variable-inductance proximity pickup is shown in Fig. 2. The measuring head comprises a small inductor wound in a half pot-core made of sintered material. If the front face of the head approaches any conducting material, its inductance changes. Magnetic materials tend to increase the inductance while non-magnetic conductors tend to decrease it. The pickup can be used for non-conducting materials providing that a small piece of metal foil can be attached to the surface. If the inductance is part of a tuned circuit, the pickup can be made very sensitive. With the model illustrated, there is no difficulty in making measurements to within 0·0001 in with an accuracy of a few parts in a hundred. The relation between inductance change and gap does not follow a linear law but the deviation is small providing that the gap is made several times the vibrational displacement. On the other hand, sensitivity greatly increases as the gap is made smaller. With this particular pickup, direct measurement of vibration amplitude is facilitated by mounting the head on a micrometer screw and fitting a dial indicator which shows the longitudinal movement of the head. If the output of the pickup

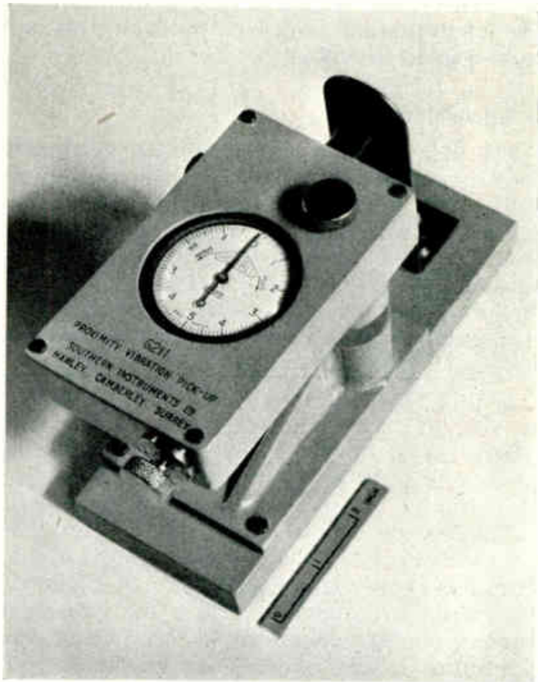

Fig. 2.—This pickup is mounted in a test stand so that the sensing head is in close proximity to a metal bracket in order to measure the amplitude of lateral vibration of the latter.

is ultimately presented as a visual waveform, it is only a matter of adjusting the micrometer screw to bring the highest and lowest peaks of the waveform successively to the same point on the record. The change in reading of the dial indicator, which may be calibrated in 0·0001 in divisions, then gives the value of the peak-to-peak vibration displacement. A similar technique may be used to determine the instantaneous displacement of any point in the vibration waveform.

2.2. *Principle of Seismic Pickups*

If a rigid mounting, isolated from the vibrating surfaces, is not available, it is necessary to provide a reference point by other means. This is the more general case and the usual method is to employ a seismic pickup. This essentially comprises a mass suspended by a compliant mounting within the pickup casing. The pickup casing is then rigidly attached to the vibrating member so that it follows the vibratory motion. The inset diagram in Fig. 3 represents this case. The frame of the pickup is subjected to the vibratory motion, any component of which may be expressed by

$$x = x_0 \sin \omega t.$$

where x = instantaneous displacement from rest position.

x_0 = peak amplitude of displacement from rest.

$\omega = 2\pi f$.

and f = frequency of the vibration component.

t = time from some arbitrary zero.

The characteristics of the mounting of the mass may be idealized into a pure compliance (a spring) in parallel with a pure velocity-damping device (a dashpot). When the frame of the pickup is vibrated, there will be relative motion between the mass and the frame. The relation between the peak amplitude of the vibration, x_0, and the peak amplitude of displacement between the mass and the frame, y_0, depends upon a number of factors. These may be defined if the ratio between the natural resonant frequency of the mass-compliance system and the damping coefficient is known. Mathematical expressions for these will be found in any textbook on vibrations. For practical purposes it can be considered that the natural frequency of the system is the frequency at which it will continue to oscillate, when once disturbed, if the damping is small. The critical damping coefficient, c_c, may be taken as a measure of the damping required just to prevent the system from being oscillatory when a sudden disturbance is applied. The amount of damping provided in the pickup is defined by the damping ratio, c/c_c, where c is the actual coefficient of damping.

The curves of Fig. 3 represent the ratio of mass-to-casing movement plotted against the ratio of vibrational frequency to natural frequency at various damping ratios. When damping is absent ($c/c_c = 0$) the familiar resonance curve results. If the vibrational frequency approaches the natural frequency of the seismic system, very large movements of the mass occur and, in theory, the movement of the mass relative to the pickup casing would become infinite when $\omega = \omega_n$. In all practical mechanisms, some damping is present. If this is carefully controlled, the other curves of the figure can be produced. As the damping increases, the amplitude of the mass relative to

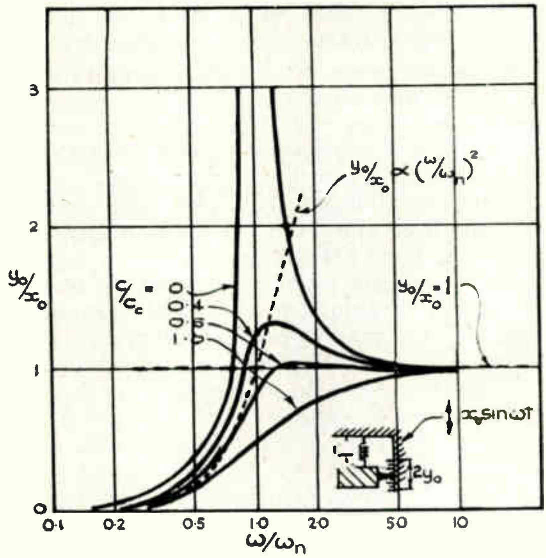

Fig. 3.—Curves relating to the seismic system, shown diagrammatically inset. They illustrate the variation of amplitude ratio with frequency ratio for different degrees of damping.

the frame decreases at resonance, until a clearly marked resonant point disappears altogether at higher values of damping. When the damping ratio is about 0·6 and the frequency of the vibration is higher than the natural frequency of the seismic system, the relative motion of the pickup mass to the frame is practically equal to the vibratory displacement of the pickup. This means that when the pickup is subjected to a vibration, the mass suspended inside it tends to stand still. It thus provides the reference point from which measurements can be made. The displacement between mass and case effectively equals the displacement of the case relative to a fixed point.

Another interesting observation which may be made from these curves concerns the behaviour of a seismic system subjected to a vibratory motion having a frequency much lower than that of the natural frequency of the system ($\omega/\omega_n < 1$). The curve for $c/c_c = 0{\cdot}6$ almost coincides with the lower portion of the dotted curve in the figure. This dotted curve is a parabola representing a relationship such that the amplitude ratio y_0/x_0 is proportional to the square of the frequency ratio ω/ω_n. Now this relationship is just that required so that the relative displacement of the mass to the frame of the pickup may be proportional to the acceleration to which the case is subjected.

A seismic pickup having a damping ratio of about 0·6 may therefore be used either as a displacement or an acceleration-measuring device. For displacement measurement, the natural frequency of the seismic system is made as low as possible and the usable range extends upwards from this. For acceleration measurement, the natural frequency is made as high as possible and the usable range extends downwards. If the natural frequency is many times higher than the vibrational frequency, the damping ratio is not critical and it may be sufficient to rely on the inherent damping within the material and construction of the unit. There is, however, a danger that in this case the mass would oscillate at its natural frequency if subjected to shocks or transient conditions and the resultant output signal would not represent the true vibratory conditions being measured.

2.3. *Electromagnetic Pickups*

There are a number of applications of the principle outlined above which are available commercially as vibration pickups. These units differ in their mechanical construction and in the electrical quantity used to measure the relative displacement between the seismic mass and the casing of the pickup. Some units use an electromagnetic system in which a coil moves in a magnetic field. Either the magnet itself may be part of the seismic mass and the coil fixed to the casing, or else the mass carries a moving coil which moves in the gap of a magnet fastened to the case. Although such units do measure vibrational displacement, the electrical output from the coil is proportional to the rate of change of displacement of the conductors in the magnetic field. The output may thus be regarded as being proportional to vibrational velocity. An integrating circuit is necessary if voltage proportional to displacement is required. A vibrating table having a known vibrational amplitude is required for calibrating these pickups, as it is not possible to do so by applying a static deflection to the mass or casing.

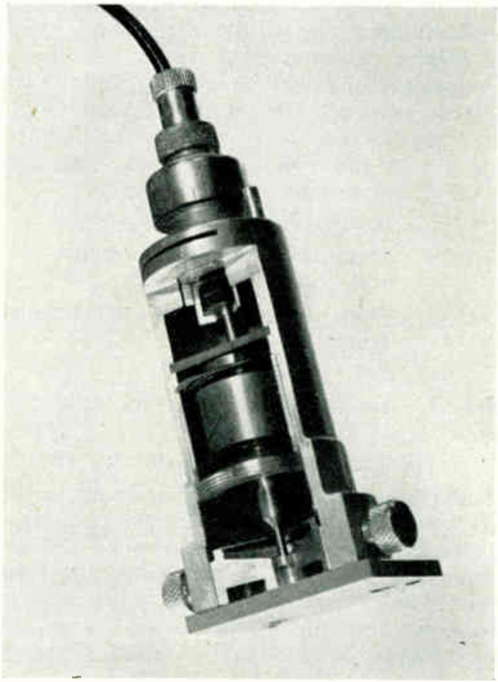

Fig. 4.—A sectional model of a seismic displacement pickup. This unit is about 5 in high.

2.4. *Variable-Inductance Pickups*

An example of a true displacement pickup is shown in cutaway form in Fig. 4. In this instance the mass is suspended on beryllium-copper spiders which allow flexibility longitudinally but which are very stiff in the transverse directions. An extension to the bottom of the mass carries a small piston which fits into an oil-filled dashpot to provide the required degree of damping. The undamped natural frequency of this system is about 12 c/s and it acts as a displacement pickup with an accuracy of 5 per cent. from 15 c/s upwards. The top of the pickup casing carries a micrometer head into which a small inductor, wound in a pot core, is fixed. A probe attached to the top of the seismic mass can move in and out of this core as the mass moves relative to the case. The incremental inductance of the coil can thus be made proportional to the movement of the mass. The pickup may readily be calibrated statically by screwing down the micrometer head an amount indicated by its engraved markings. This causes the inductor to move towards the mass and thus results in a sustained increment of inductance. With suitable electronic circuits this can be made to give a steady reading of the recording device and thus to indicate the overall calibration factor of the equipment.

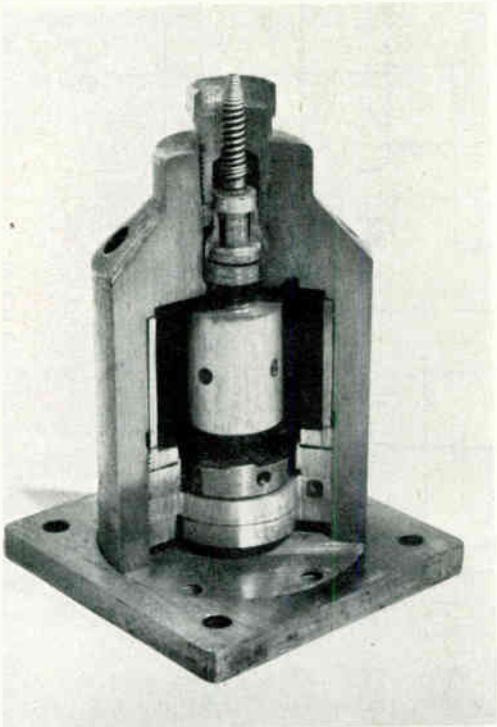

Fig. 5.—A sectioned pickup which acts as a seismic accelerometer. The base of the unit is 2½ in square and a coaxial cable connector is provided at the top.

2.5. *Variable-Resistance Pickups*

Pickups having a natural frequency above their operating range may be of many types. In one, the mass is suspended by filaments of resistance wire which therefore act both as the mechanical compliance and the electrical sensing element. Movement of the mass relative to the casing results in a change in length of the filaments. The resistance wires are connected in bridge form so that bridge unbalance is proportional to the acceleration to which the pickup is subjected.

2.6. *Variable-Capacitance Pickups*

A variable-capacitance accelerometer is shown in Fig. 5. A lapped circular diaphragm is clamped at its periphery and is loaded by means of a mass held against it by springs. The seismic system is composed of the mass and the compliance of the diaphragm. The natural frequency of this system may be 10 kc/s or more and it will withstand and measure accelerations of 500 *g* or greater. The deflection of the diaphragm relative to the case is detected by an insulated electrode spaced a few thousandths of an inch from it. Deflection of the diaphragm causes the electrical capacitance between it and the insulated electrode to alter and this can readily be measured by suitable circuits.

2.7. *Piezo-Electric Pickups*

Piezo-electric materials have been used in several kinds of accelerometer. Usually the piezo-crystal itself acts as a mechanical compliance and the seismic mass may either be composed of the mass of the crystal itself or comprise an additional weight held in contact with it. The voltage output of a well-designed device of this kind is directly proportional to the applied acceleration, with the lower limit of frequency determined by the time-constant of the crystal and its associated circuits.

3. Pre-circuits

It has already been mentioned that the sensitive elements of vibration pickups may be "generating" or "passive." For "generating" pickups, in which the output is a voltage related to the vibration amplitude, a stable, wide-range amplifier is required. This amplifier should be designed to match the impedance of the pickup and have an output suitable for feeding to the next amplifying stage. Recently a number of ingenious circuits have been developed for this work. In some, a carrier current is employed which is modulated by the signal voltage. This enables high gains to be obtained. A more straightforward approach employs d.c. amplification with special means for ensuring that drift of the amplifier is reduced to a minimum. It will be appreciated that if the output of a d.c. amplifier tends to drift due to temperature, supply voltage fluctuations, or ageing of the valves, a spurious signal, corresponding to a slow change

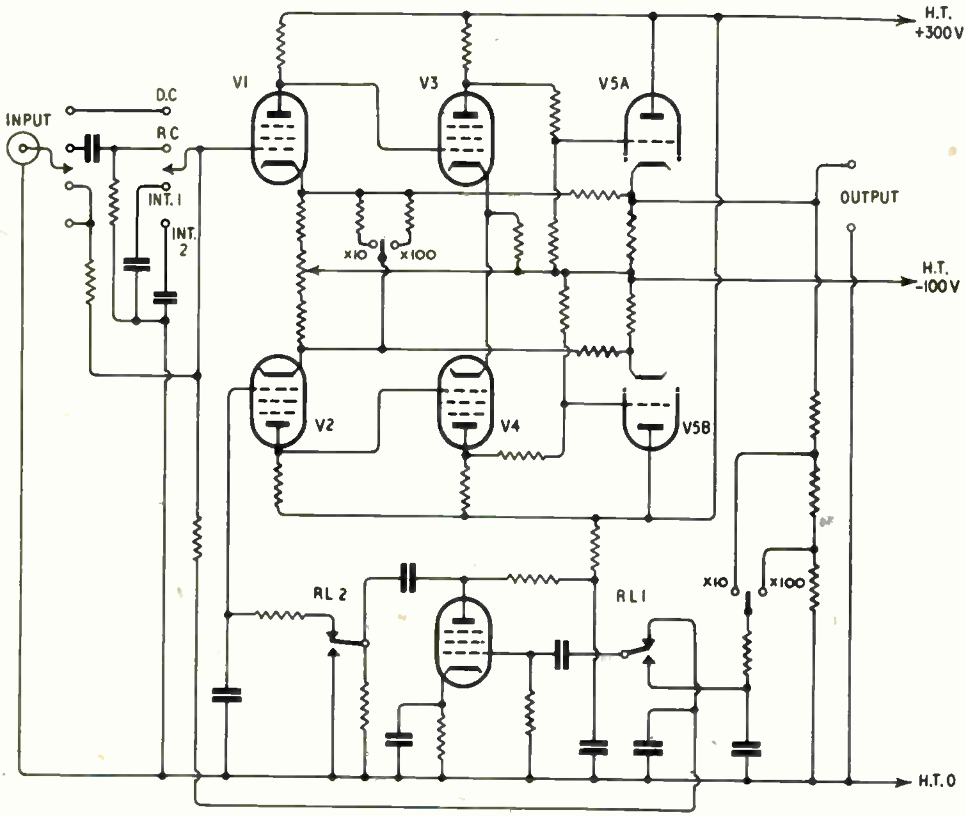

Fig. 6.—Schematic circuit diagram of a drift-corrected, direct-coupled preamplifier.

in output from the pickup, is produced. As a consequence, most d.c. amplifiers employ balanced circuits and necessitate thorough stabilization of power supplies.

3.1. *Direct-Coupled Preamplifier*

One d.c. amplifier with means for preventing drift is shown in Fig. 6. The gain of this amplifier may be selected at 10 or 100 by the front-panel switch. It responds to d.c. levels as well as having a response flat to 50 kc/s. An additional circuit is provided for the continuous correction of any drift. The mode of operation of the circuit is as follows: Valves V1, V2, V3 and V4 form a fairly conventional balanced direct-coupled amplifier with a substantial degree of negative feedback. The input signal is applied between earth and the grid of V1. Provision is made for direct-coupling, capacitance-coupling or two alternative integrating couplings of the input signal. The gain is adjusted by changing the value of the resistors coupling the cathodes of V1 and V2. V5 is a double triode cathode follower stage, also direct-coupled, and the output is taken from the cathode of V5A only. A fixed potentiometer across the output and having an attenuation numerically equal to the gain of the amplifier feeds through a resistance-capacitance filter to one contact of a Carpenter relay (RL1). The other contact of the relay is fed through a similar resistance-capacitance filter from the amplifier input. The relay coil is driven from the low-tension a.c. supply. The grid of V6 therefore receives 50 c/s square waves whose amplitude depends upon the drift which has occurred between the input and output of the amplifier. These square waves are amplified by V6 and rectified by a second relay (RL2) operated in synchronism with the first. The resulting d.c. drift-correcting signal is applied to the grid of V2 so as to restore the d.c. balance of the amplifier as a whole. It will be appreciated that this in fact constitutes a feedback circuit which reduces drift by a factor equal to the

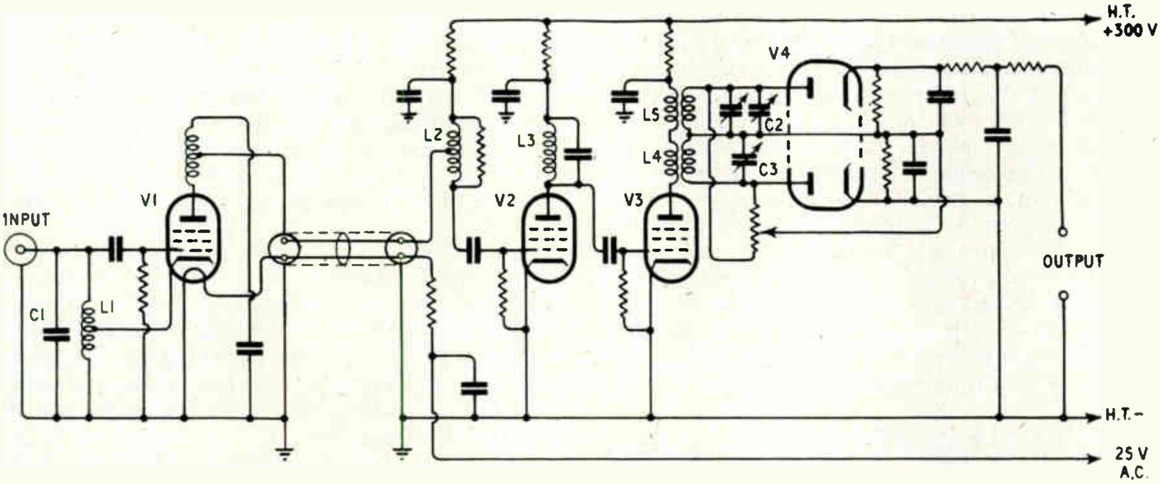

Fig. 7.—The basic circuits of a frequency-modulation system for use with variable-reactance pickups.

amplification of the V6 stage. It does not, of course, apply a correction for changes in output level consequent upon a change of d.c. level at the input terminal. The amplifier therefore responds to sustained voltage inputs in the normal manner.

Pickups having a "passive" element require some energizing or carrier voltage. In some instances, a d.c. supply may be used, in which case the changes caused by the measured physical quantity result in a voltage signal. For instance, a variable-resistance pickup may be connected in a d.c.-excited Wheatstone's bridge and the bridge output be fed to a preamplifier of the kind just described. Alternatively, a.c.-excitation may be used, so that an amplitude-modulated carrier signal is produced. This latter method has the limitation that the frequency of the vibration must be appreciably less than the frequency of the carrier. It is not usually practicable to make the latter more than about 5 kc/s.

3.2. *F.M. Carrier Preamplifier*

With variable-inductance and variable-capacitance pickup elements, it is usually possible to arrange for a carrier of much higher frequency to be used. In one system, a carrier frequency of 2 Mc/s is employed and this is frequency-modulated by the change of reactance of the pickup element. The basic circuits of the equipment are shown in Fig. 7.

The oscillator valve, V1, and its associated components are contained in a small cast aluminium box located close to the pickup. The latter is connected to the input terminal by a length of heavy duty coaxial cable. The reactance of the pickup element is thus in parallel with the oscillator tuned circuit C1, L1. In practice a number of alternative capacitors are provided for C1. The oscillator can therefore be made to generate a signal close to 2 Mc/s in frequency, providing that the total inductance or capacitance of the cable and pickup are within prescribed limits. Small changes in the reactance of the pickup thus cause corresponding changes in the oscillator frequency. The oscillator is connected to the rest of the equipment by a twin-conductor shielded cable of any desired length. This cable carries both the frequency-modulated signal from the oscillator and also the power required for V1. The amplifier-discriminator comprises two amplifying and limiting stages, V2 and V3, which are coupled by tuned circuits, L2 and L3. The transformers L4 and L5 are adjusted to resonate at slightly different frequencies. A tuning control, C2 and C3, enables the centre frequency to be tuned so that it is equal to the mean output frequency of the oscillator. V4 is a two-diode discriminator which rectifies the output from the transformer secondaries connected in series. Within the desired limits, the output voltage from the discriminator is directly proportional to the deviation of the oscillator frequency from its mean. The circuit values used in practice enable an output of 10 volts to be obtained for a capacitance change of 5 pF at the pickup. Other refinements include a cathode-follower output stage after the r.f. resistance-capacitance filter which follows V4, and a voltage calibrating circuit which enables steady changes at the pickup to be read off as arbitrary divisions on the dial of a precision potentiometer. This enables the "static calibration" facility of many types of pickup to be fully exploited. For instance, in the case of the seismic accelerometer pickup described earlier and illustrated in Fig. 5, the pickup may be calibrated by subjecting it to a known steady acceleration on a rig or in the earth's gravitational field. The resulting output

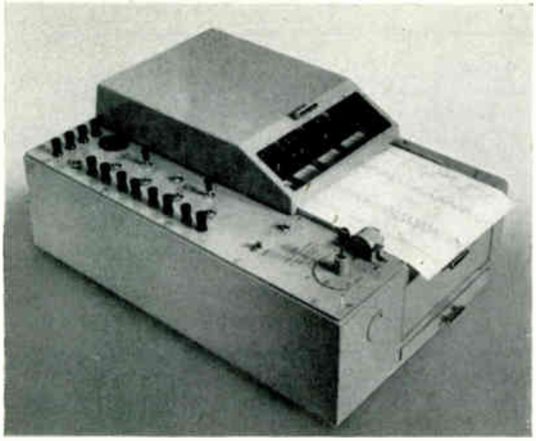

Fig. 8.—A four-channel direct-writing pen recorder in which the ink record is immediately available for study and measurement.

voltage from the f.m. system can be measured on a meter and backed off to zero by means of the calibration control. Subsequent observations of the pickup's output under test conditions can then be calibrated by superimposing steady voltages obtained from known settings of the calibration control.

Another advantage of this f.m. system is that the cable between the oscillator and the rest of the equipment may be of almost any desired length—certainly up to many hundreds of yards. The essential quality of the signal at this point is its *frequency*, and no changes in its amplitude, losses in the cable, or the picking-up of interference or hum can affect this and hence introduce distortion. Furthermore, the small amount of power required by the oscillator is carried along this cable and so the oscillator itself can be made conveniently small, while the power may be supplied from a pack that is located with the rest of the equipment. Admittedly the coaxial cable between the oscillator and the pickup must be relatively short and stiff and not likely to change in impedance with vibration. Fortunately, this is not usually difficult to arrange.

4. Amplifiers

"Driver" amplifiers for vibration recorders conform in most respects to conventional practice, and therefore will not be dealt with in detail here. It is often advantageous to have direct coupling between the valves of the amplifier so that the output is responsive to sustained inputs. This enables full use to be made of pickups and their associated pre-circuits which respond to sustained physical effects. The matching of the output of the amplifier to the recording device is important and valves of adequate voltage- or power-handling capacity must be used to ensure a low degree of distortion.

5. Recorders

The simplest form of recorder is a deflectional meter. Depending upon the circuit in which it is connected, the pointer may indicate the total vibration amplitude, or the so-called r.m.s. value. This may be quite sufficient in many cases, when the total amplitude of a vibrating part may be taken as an indication of the running condition of machinery.

If an analysis of the vibration into its component frequencies is required, an electronic analyser may be used in conjunction with the simple vibration meter just described. Such an analyser comprises some form of tuned amplifier with a suitable output meter. As the tuning of the analyser is varied throughout its range, each component of the vibration is picked out in turn, its frequency read from the tuning dial and its relative amplitude indicated on the meter. Such a system is only useful if the vibratory conditions are steady for a sufficient length of time for the complete vibration spectrum to be explored in this manner.

Visual presentation of the waveform is usually much easier to appreciate qualitatively, and is obtainable more quickly than the results from the usual electronic analysers. The computational work involved in obtaining a quantitative analysis from a visual waveform is, however, much greater. In many engineering

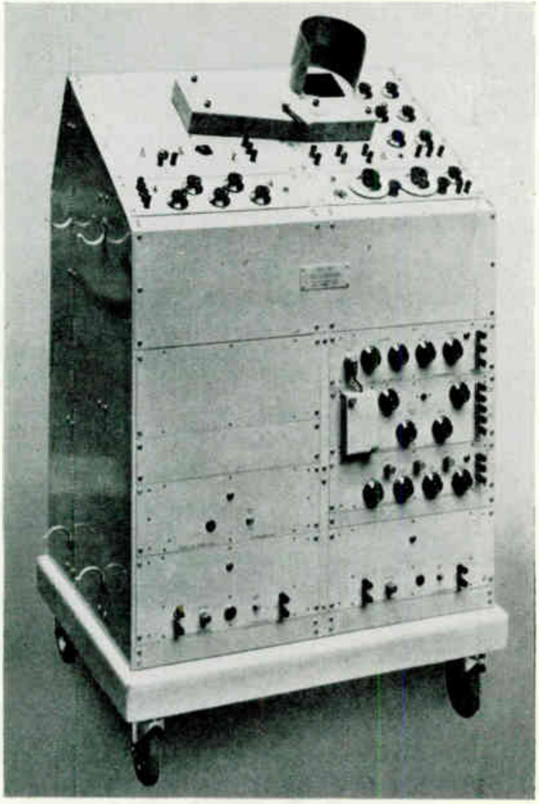

Fig. 9.—A trolley-mounted cathode-ray oscillograph which is complete with all amplifiers, time-base generator and power supplies. A recording camera is also built in.

applications, however, the shape of a waveform to an experienced eye can reveal more than the elaborate expression of the vibration in the mathematical terms of its Fourier components.

A direct-writing recorder may be used for frequencies up to about 100 c/s. This type of instrument comprises a pen arm driven by an electromagnetic system while a motor carries recording paper past the pen in a direction at right angles to the pen movement. Ink, wax or electro-chemical methods may be used to give a legible trace on the recording paper but in all cases the record is immediately visible without further processing. Fig. 8 shows a four-channel ink recorder.

For higher frequencies, photographic methods of recording are inevitable, with inherent delay due to processing of the record before it can be permanently seen and stored. Using "light beams" as magnifying levers, Duddell galvanometers can be used to record waveforms photographically up to frequencies of several thousand cycles per second. A multi-channel equipment of this kind is compact and relatively light in weight and has been found invaluable for making records of vibrations in aircraft during flight.

The most versatile of all recorders is the cathode-ray oscillograph. Its frequency range extends from zero up to 100 kc/s or more without difficulty. The vibration waveform which it presents may be immediately studied visually or recorded by means of a simple camera added on to the face of the cathode-ray tube. Time or event marks can readily be superimposed electronically on the vibration signal so that frequency, time or phase measurements may be made directly from the screen. Cameras which feed the sensitized film continuously past a lens enable high writing speeds

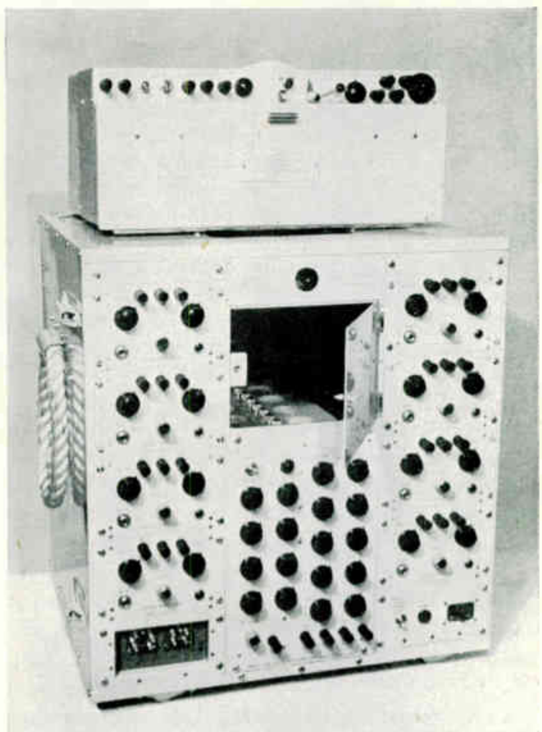

Fig. 10.—This multi-channel cathode-ray oscillograph has a continuous-feed film recording camera, fitted to the top, which photographs nine channels simultaneously.

to be achieved and thus the highest frequenc components of a vibration may be resolved.

Portability of cathode-ray oscillographs may present a problem if a comprehensive recorder is required. It is of assistance if the camera is built into the equipment and the whole mounted on a trolley as shown in Fig. 9. This equipment is built entirely in rack-and-panel form so that it is flexible and versatile without being cramped.

6. Conclusion

Increasing accuracy and robustness of pickups are likely to result from development work now proceeding. Most of the principles of design are well known but there is still wide scope for ingenuity in their application. Reductions in size and weight would be an advantage for most applications and an increase in useful frequency range would be an added attraction.

The pickups, however, are only a small physical part of a complete vibration recording equipment, though they are often the most critical as regards dimensions. Nevertheless, it is to be expected that the electronic part of equipments will become smaller and lighter in time and that they will become more and more accepted as a convenient tool by mechanical engineers in many fields, of which vibration measurement is but one. An example of latest practice is shown in Fig. 10. This has eight simultaneous recording channels and a ninth cathode-ray tube on which time or event marks may be displayed. The unit contains all the driver amplifiers and tube controls and a continuous-feed recording camera is mounted at the top. Optical systems enable all the cathode-ray traces to be recorded in correct phase relationship to one another. The complete equipment weighs about 170 lb.

7. Acknowledgment

The author is grateful to Messrs. Southern Instruments, Ltd., for their assistance and for permission to publish this paper.

DISCUSSION

J. A. Sargrove (Member): I would like first of all to congratulate all four authors on a wonderfully brief and lucid combined lecture. Perhaps the following problem is quite commonplace in the field of vibration measurement, but I would like to know whether it is possible to make a transducer which combines a vibration generator as well as a vibration pick-up. There are certain industrial applications in which I am interested in which such a device would be most useful, particularly if it were very small.

H. Moore (*in reply*): The illustration of the large model (Fig. 1) did, in fact, include a vibration pick-up and these have also been used on smaller generators. There is a limit to how small the pick-up can be made, but the size will be dependent on the amount of force you wish to produce and also on the required sensitivity of the pick-up coil.

W. L. Oliver: I had hoped we would hear something about measuring displacements at higher frequencies. Have the authors anything to suggest for displacements in the 8 to 10 kc/s region?

R. K. Vinycomb (*in reply*): There is no fundamental reason why one should not measure displacements in that range. Usually in engineering one finds that as the frequency goes up the amplitude goes down, but if one uses an accelerometer there is no reason at all why displacement can not be measured at very high frequencies. Piezo-electric crystal accelerometers have been used up to this order of frequencies.

D. A. Drew: Might I ask Mr. Moore why so many engineers responsible for the design of vibrators recommend their operation only at such low frequencies? He does not recommend his vibrator for frequencies in excess of 5 kc/s, although I can say from first-hand experience that they are very effective at much higher frequencies.

Another point I would like to raise is that manufacturers in describing their products refer so much to the forces available. Surely the most useful figure of merit is the acceleration that can be obtained from a moving system. This acceleration is clearly the force divided by the mass of the moving element. This is really the figure of merit on which one would like to buy a vibrator.

H. Moore (*in reply*): The answer to the first part of the question is closely linked with the second part. Working at much higher frequencies involves stiffening and consequently making heavier the moving part of the vibrator itself, thus lowering the force to mass ratio which must be kept high to get very high accelerations. In the case of the smaller units which can be relatively more compact and stiffer, operation is possible up to 10 kc/s, or even beyond. There are developments in vibration methods for the ultrasonic frequencies, but they usually involve operation at a fixed frequency. If one wishes to maintain the non-resonant type of vibrator which will cover a large band of frequencies, the moving-coil type appears to be the only practical solution at the present time.

J. Southwell: I should like information on the particular problem of the measurement of torsional vibration.

P. Jackson (*in reply*): One answer to the torsional vibration measurement problem is based on the use of phonic wheel generators, which incidentally avoids the slip-ring troubles associated with strain-gauge methods. A single wheel is used and its output treated as an f.m. carrier, modulated by the frequency changes due to torsional vibration. It can be done and we have developed a system which is not, however, available commercially.

C. A. Meadows (Associate Member): Mr. Vinycomb referred to measuring amplitudes, and so on. Can he suggest how the pick-ups can be calibrated up to those high frequencies?

R. K. Vinycomb (*in reply*): Calibration at high frequencies is a difficult problem and one has to do a little judicious extrapolation. One advantage about accelerometers with passive elements is that you can calibrate them by turning them upside down. We have to rely on the vibration generators of Mr. Moore's company for dynamic calibrations; we measure the displacement of the vibration generator and convert that to acceleration.

C. R. Maguire: In connection with the last question, there is a method of calibration at high frequencies up to 20 kc/s using the principle of reciprocity, in which voltage is applied to one transducer and the resulting voltage from the other is measured. If you have, say, two accelerometers coupled back to back as in a Hopkinson test and supply constant voltage to one, the signal from the other should be directly proportional to the square of frequency. If a constant voltage is supplied at various frequencies and the output plotted, then any resonance in the accelerometer will produce a kink on the curve. The difficult part of it is that if there is, say, 100 V on one side, then, at 1 kc/s with the particular type of accelerometer I have got in mind, one micro-volt is obtained on the other side, giving an attenuation of something like 10^8 in the system.

C. G. Mills (Graduate): On the subject of high frequencies, we have developed a photo-electric vibration meter which utilizes a parallel beam of light interrupted by a vane. By letting the light fall on a photo cell and blocking off the d.c. component, it is possible to determine the varying displacement and, as a vacuum photo cell is not frequency-sensitive, it is possible to go up into the tens of kilocycles region. The frequency limit is only dependent on noise which is a very serious restriction. For instance, at 1 kc/s and a displacement of 1/1,000 in peak-to-peak, we get a noise figure of 1·6 per cent of the signal.

C. R. Little: In view of the high current requirement, could we have some information as to the battery capacity used with foil types of strain gauges. I feel we should probably end up with a load of 2 cwt or so of batteries for a multi-point installation.

P. Jackson (*in reply*): This supposition may well be correct, but I think that one would prefer 2 cwt of batteries to 2 cwt of electronic equipment.

H. W. Taylor: I am interested in the problems of recording stresses or strains at very high temperatures. I believe Mr. Jackson said strain gauges had been used up to several hundred degrees centigrade. Could he amplify that statement?

P. Jackson (*in reply*): For high-temperature work one has to depart from the normal strain gauge backings, cellulose acetate and paper, bakelized paper, Araldite, etc., and use a transfer process. The strain gauge is made on a very thin collodion backing and a ceramic cement (Quigley's No. 3, or Saurreissen) is used as an adhesive. The gauge is applied, backing upwards, to a thin layer of cement on the specimen. Air drying usually gives sufficient adhesion to permit the collodion to be swabbed off with acetone, and after allowing the acetone to evaporate out completely another layer of ceramic cement is applied. The bonding process is then completed as recommended by the cement manufacturers. The gauge is then invested, as it were, in a ceramic coating bonded quite well to the specimen. It is a very tricky operation, but it can be done.

S. Molian: One of the speakers mentioned ultrasonics. I do not know if the information would be of interest to anyone here, but I would point out that there are quite simple ultrasonic pick-ups, using quartz or barium titanate crystals. Vibrations are produced and picked up by the crystals at frequencies up to 10 Mc/s. A frequency of about 2 Mc/s is the most common in this work.

A Visitor: I would like to ask Mr. Jackson about the value of resistance of the foil strain gauges. At the present point in development I believe this is rather low, and hence there are difficulties caused with ordinary types of electronic equipment. The wire-wound type is the more general one at the moment, but I feel if the foil gauge could be used with high resistance its other advantages would bring it to the fore. I would like to know if there are any further developments.

P. Jackson (*in reply*): I agree that the resistance has got to go up and we think that possibly in the very near future we shall be able to increase it up to several times the present value. Fortunately all users of gauges are not in the same case, as for instance in static strain measurement applications where gauge resistance is relatively unimportant.

J. Skorecki: Can either of the speakers recommend a method of reproducing the vibration after having it recorded on the road, using, for instance, a vibration generator?

H. Moore (*in reply*): If you mean producing exactly the wave form of the vibration you meet on the road, I think the answer is the same as in the analysis of the vibration wave forms. We have to analyse them into a Fourier series of single frequency waves, and if you want to reproduce these conditions you can reproduce each frequency separately. If you wish to go to a lot of trouble you can reproduce them simultaneously through a vibration generator, but, in general, it is believed that if you apply the single frequencies separately at the levels they have been analysed in the wave form a satisfactory result is obtained.

S. Molian: If you want to build up a complex vibration with two or three components, and you could produce each of these components with a vibration generator, how would you do it?

H. Moore (*in reply*): You would combine the frequencies in the electrical stage, rather than in the mechanical, but I do not think this practice is adopted very widely. Single frequency excitation is usual, although by modern electronic methods it is possible to add amplitudes, and so on, and then, provided the amplifying equipment can cope with the subsequent wave form, it can be applied to the vibration generators.

W. Bryant: In the checking of road vehicles, for vibration the problem usually is the determination of transmission resonance. It may be of interest that recently the source and cause of transmission of body resonance of a motor car was traced by putting the car on jacks, applying a high-power vibrator to the back bumper. The frequency was varied slowly through the range until the body resonances were not only audible but could be felt.

W. T. Kirkby: I would like to ask the authors whether they have any views on methods of playing back records into analysers. In general, it is far easier to get a vibration record than to analyse it afterwards. Mr. Vinycomb showed us the signal being fed directly into an analyser, which is, of course, the ideal system. Unfortunately, in our particular application—which is for aircraft—we cannot fly the analyser and, therefore, we have to seek some way of analysing the record subsequently on the ground. We are particularly interested in the frequency range from 2 c/s to perhaps 25 or 30 c/s, and, in general, there do not seem to be small enough analysers available for the lower frequency end. Have any of the speakers comments to make or suggestions for playing back records into the analyser ?

R. K. Vinycomb (*in reply*): I cannot really appreciate the point why you cannot fly an analyser, as it does not weigh any more than a recorder, and there is certainly a suitable analyser going down to 2·5 c/s. Recording on tape has been done, but there are a lot of limitations. You have got to ensure an adequate frequency response and you must know at what level you are recording and reproducing.

G. Stearman: May I say that my firm is developing an instrument which can follow line records on film, so that a 35-mm transparent film record can be reproduced on a cathode-ray tube by causing the spot to follow the line. This may be done on the ground, and the output then used for correlation, etc.

P. Jackson (*in reply*): Strain gauge techniques have been successfully applied to telemetering vibration information from the turbine blades of an aircraft in flight. The information was tape recorded for analysis on the ground.

D. A. Drew: We have telemeters in flight at 40,000 ft and we have recorded frequencies on paper up to about 15 kc/s, and I do not think that this is the limit.

INSTITUTION NOTICES

Obituaries

The Council of the Institution has expressed its sympathy with the relatives of the following members:

Boleslaw Dulemba (Member), who died on January 3rd at the age of 41 years, was born in Warsaw in 1912, and was educated at the Wawelberg and Rotwand Technical School of Radio Engineering. Mr. Dulemba received his technical training with Philips, Warsaw, and was for three years with the A.V.A. factories for special radio development work and production; he held a number of patents relating to radio transmitters. From 1938 to 1944 he was chief of the technical department for radio communications with the Polish Government in London, and after the war joined the Romac Radio Corporation in London. In 1947 he went to Brazil to found his own company, Electrofone Sociedade Comercial e Tecnica Ltda of Rio de Janeiro. He is survived by his widow and one son.

Mr. Dulemba joined the Institution as an Associate Member in 1945 and was transferred to the class of Member in 1947.

Vernon Hollos Haigh (Associate) was born at Huddersfield in 1915 and served in the Royal Air Force during the war as a Sergeant Instructor. Following an illness lasting five months, Mr. Haigh died on November 30th last as a result of cancer of the lung. Since June, 1952, he had been with the War Department at Killingworth, near Newcastle upon Tyne, holding the rank of Technical Assistant Grade I. He leaves a widow and two young sons.

Mr. Haigh was elected an Associate of the Institution in 1949.

Subscription Renewal

All grades of members are reminded that subscription renewals are due on the 1st April, 1954. It would greatly assist the work of the Institution if members would remit their subscriptions as near as possible to the due date.

As indicated in the last Annual Report (September, 1953, *Journal*), only 770 members gave donations to the Benevolent Fund—the lowest percentage ever recorded. A special appeal is made this year, therefore, for all members to include with their annual subscription a donation to the Benevolent Fund.

May, 1954, Graduateship Examination

The next examination will be held on Wednesday, Thursday and Friday, May 19th, 20th and 21st, 1954. Entries for this examination from *home* candidates should be lodged with the Institution not later than April 1st, 1954.

The closing date for *oversea* candidates for the November, 1954, examination is May 1st, 1954.

Physical Society Exhibition

As announced in the January *Journal*, the Physical Society Exhibition will be held at Imperial College, South Kensington, London, S.W.7, from Thursday, April 8th, to Tuesday, April 13th.

The Institution has received a limited number of tickets for the use of members only and requests for these should state clearly on which day it is intended to visit the Exhibition.

The tickets are split into four groups as follows:

(1) Whole day tickets which are available for *any one* day of the Exhibition.

(2) Season tickets which can be used on all three evenings on which the Exhibition is open.

(3) Morning tickets which can be used on any one morning.

(4) Tickets are also available which give admission on Saturday only.

The morning of Thursday, April 8th (10 a.m. to 2 p.m.) is reserved for Fellows and Press only.

Discourses will be given at 6.15 p.m., as follows:

Thursday, April 8th.—"Electrical Contacts," by Professor F. Llewellyn Jones.

Friday, April 9th.—"An Artificial Talking Device," by Mr. W. Lawrence.

Monday, April 12th.—"The Study of Surface Micro-topography by Optical Methods," by Professor S. Tolansky.

Radio Components Show

The 1954 Radio Components Show will be held from April 6th to 8th inclusive, at Grosvenor House, Park Lane, London, W.1. The times of opening were given in the February issue of the *Journal*, page 50, and the Institution has a *limited* number of tickets for the use of members.

NEW BRITISH STANDARDS

The British Standards Institution has recently issued the following new and revised Standards, copies of which may be obtained from the British Standards Institution, Sales Branch, 2 Park Street, London, W.1. The Brit.I.R.E. is represented on the Technical Committees which were responsible for those Standards marked with an asterisk (*).

B.S. 308 : 1953. **Engineering Drawing Practice.** Price 10s. 6d.

Any progress towards a universal drawing practice is of profound importance to engineers, and the publication of a new and far more comprehensive edition of B.S. 308, "Engineering Drawing Practice" is undoubtedly a prominent milestone on the road toward obtaining a universal engineering language.

The new standard is divided into two sections. Section One (General Practice) is based on the previous B.S. 308 : 1943, and deals with recommended principles and methods to be followed in the preparation of engineering drawings.

Section Two (Dimensioning and Tolerancing) is entirely new, and presents a great advance in the technique of drawing statement. It lays down a number of general principles, of which the most important are that the drawing should define the finished product as required by the designer, and that dimensions which affect the functions of the product should be expressed directly on the drawing. The concluding parts of the standard cover the dimensioning and tolerancing of profiles, and the indication of machining and surface finish.

B.S. 530 : 1948. Supplement No. 3. **Additional Symbols for Electronic Tubes and Valves including Gas Switches.** Price 2s. 6d.*

The current edition of B.S. 530 is incomplete in respect of the graphical symbols used in very high frequency technique and gas-filled cold-cathode discharge tubes in which there has been unusually rapid development in recent years.

Supplement No. 3 gives graphical symbols for:—

(*a*) Various electronic tubes and gas switches used particularly in radar technique.

(*b*) Gas-filled cold-cathode discharge tubes.

The graphical symbols for gas switches are a logical development for the symbols given in Supplement No. 2 "Graphical symbols used in Waveguide Technique." The symbols for gas-filled cold-cathode discharge tubes are based on current British and American practice; some slight amendments to the existing symbols in B.S. 530 are necessary to meet developments and are included in this supplement.

B.S. 448 : 1953. **Electronic-valve Bases, Caps and Holders.** Price 22s. 6d. (including binder).*

The revised standard specifies such physical requirements of bases and caps of electronic valves, and in some cases their outlines and associated holders and connectors, as are necessary for mechanical compatibility and satisfactory electrical contact. These requirements are defined, with a few exceptions, by means of gauges.

The standard is published in loose-leaf form to facilitate amendments and additions.

B.S. 727 : 1954. **Characteristics and Performance of Apparatus for Measurement of Radio Interference.** Price 4s.*

The equipment described is now suitable for the measurement of radio noise in the frequency range of 150 kc/s to 150 Mc/s. A more detailed specification of the performance of noise-measuring equipment replaces the somewhat loose specification, and the example of a suitable measuring set, given in the 1937 edition.

The apparatus specified is intended for the measurement of radio frequency noise field strength or terminal voltages. The specified bandwidth and time constants of the relevant sections of the receiver, and the characteristics of the indicating instrument, are such that the readings obtained are a measure of the annoyance effect of the interference. Radio noise voltages and fields are measured in equivalent root mean square microvolts and microvolts per metre respectively, i.e. the measuring set is calibrated in terms of the r.m.s. value of a sine wave voltage and the indicated voltage of any given noise voltage is therefore the r.m.s. value of a sine wave voltage which would give the same indication. It is emphasized that the indications are not the r.m.s. value of noise voltages.

The wide frequency range specified (150 kc/s–150 Mc/s) cannot be covered without changing some of the characteristics of the measuring equipment. The change has been made at a frequency of 30 Mc/s and certain clauses therefore specify different characteristics for the frequency ranges of 150 kc/s–30 Mc/s and 30 Mc/s–150 Mc/s.

B.S. 800 : 1954. **Limits of Radio Interference.** Price 4s.*

B.S. 800, Limits of radio interference, has now been revised and extended to cover the existing television frequency band of 40 Mc/s to 70 Mc/s. The Standard specifies the limits of magnitude of radio-noise terminal voltages and radio-noise fields throughout the ranges 200 kc/s to 1,605 kc/s and 40 Mc/s to 70 Mc/s. Different limits are prescribed for these two ranges.

The limits apply to equipment directly connected to distribution systems having a declared voltage between conductors of not greater than 500 V, or a terminal voltage between any one conductor and earth of not greater than 250 V. The limits for radio-noise fields also apply to electrical equipment which is entirely self-contained, i.e., which is not connected to electric supply mains, except motor vehicles and internal-combustion engines, electrical equipment installed on ships, electrical traction systems and equipment intended for the generation and application of radio-frequency energy.

The limits are regarded as a reasonable compromise between the interests of users of radio frequency telecommunication services in these bands, e.g. sound broadcasting and television on the one hand, and those of the makers and users of electrical appliances on the other. The limits are expected to protect the majority of broadcast receivers, including television receivers, from interference when receiving programmes from appropriate transmitters in the United Kingdom. The prescription of limits low enough to give such protection to all broadcast services including that in areas of low field strength, is at present considered impracticable for economic and manufacturing reasons.

For similar reasons, in particular the cost of adequate testing, it is at present considered impracticable to prescribe, as a condition of compliance with the present standard, limits for the whole of the frequency range from 200 kc/s to 100 Mc/s or higher. Certain of the frequencies, which are at present excluded from this standard, are used for services concerned with the safety of life, and others are used for broadcasting and other essential services. Measures taken to suppress interference over the frequency ranges covered by this standard will offer some protection at other frequencies and it is highly desirable that such measures should, as far as is practicable, be so designed that the limits prescribed for the range 200 kc/s to 1,605 kc/s are not exceeded over the wider range of 200 kc/s to 30 Mc/s and that the limits prescribed for the range 40 Mc/s to 70 Mc/s are not exceeded over the range 30 Mc/s to at least 100 Mc/s.

B.S. 1133. Sec. 19 : 1953. **Packaging Code—Use of Desiccants in Packaging.** Price 3s.

The deterioration of the contents of packages is of concern to all packers, but in particular to exporters. Metal goods are liable to corrode in damp and humid climates, and some articles can be given protective treatment during manufacture, and others can be protected by the application of corrosion preventives, etc. Some, however, such as delicate instruments, cannot be given any such treatment, and for these it is essential to ensure that the humidity within the package remains reasonably constant.

The type of packaging which achieves this is known as a desiccated package, and this new section of the Packaging Code describes the method, deals with factors governing the choice of desiccant, the determination of the quantity needed and other general packaging considerations.

Other sections of the Code dealing with protection of contents against deterioration are:—

Section 5. Protection against spoilage by micro-organisms, insects, mites and rodents. Price 2s.

Section 6. Temporary prevention of corrosion of metal surfaces (during transportation and storage). Price 10s. 6d. (See *Journal* for July 1953, page 376.)

B.S. 2065 : 1954. **Glossary of Terms for the Electrical Characteristics of Radio Receivers.** Price 6s.*

The electrical characteristics of radio receivers are defined and described in a form permitting the standardized measurement and description of their performance. The standard does not specify the methods of measuring the defined quantities, and, although a method of measurement may be implied in a definition, any method may be used provided the defined quantity can be diverted, directly or indirectly, from the observations.

The definitions are expressed in a generalized form so as to be applicable to many types of receivers. They do not, however, cover all characteristics of certain special types, such as diversity receivers.

THE PROPERTIES AND MANUFACTURE OF PIEZOELECTRIC QUARTZ CRYSTALS*

by

H. L. Downing, B.Sc.†

SUMMARY

The paper discusses the basic electrical properties of quartz crystals, such as frequency stability, temperature coefficient and activity. Their relationship to the actual frequency of oscillation of a crystal oscillator is described and some typical figures given.

1. Introduction

To the geologist a quartz crystal is a crystal of silica having a certain well-defined shape. A perfect specimen is a hexagonal prism terminated at each end by a hexagonal pyramid as shown in Fig. 1. But to the radio engineer, a quartz crystal is a component which, when connected into an oscillator prepared for it, maintains the frequency of oscillation constant within very close limits.

It is the purpose of this paper to discuss the basic properties of quartz crystals as they affect the performance of crystal oscillators in the frequency range 1 to 10 Mc/s. The properties with which we shall be concerned are as follows:—

1. Physical appearance.
2. Electrical equivalence.
3. Frequency.
4. Frequency stability.
5. Activity.

2. Physical Properties

2.1. *Physical Appearance*

Quartz crystal elements are normally supplied in holders of varied shapes and sizes ranging from large temperature-controlled types to miniature types. Three common types of non-temperature-controlled or "cold" holders are shown in Figs. 2 and 3. Figs. 2a and 2b show two samples of the moulded bakelite type, while Fig. 3a shows the metal can type (referred to later as a Type D holder). Two samples of the glass envelope type appear in Figs. 3c and 3d. Although these units vary in shape and size they all have one thing in common—they contain a sandwich made up of two electrodes and a piece of quartz.

The piece of quartz is usually rectangular in shape, of cross-sectional area approximately 0·2 to 1 in^2 and of thickness 0·006 to 0·06 in.

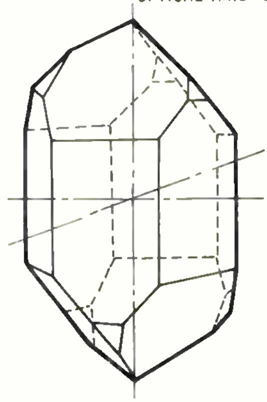

Fig. 1.—Outline of a crystal of quartz.

The electrodes can be divided into two classes:—

(*a*) Those deposited onto the face of the crystal,

(*b*) Those made from sheet metal.

The electrodes of class (*a*) are films of gold, silver or aluminium deposited directly onto the faces of the crystal as shown in Fig. 3b. The thickness of the film is of the order of 10^{-5} in, and it may cover a portion or the whole of the face of the crystal. The electrodes of class (*b*) are usually made from chemically stable and

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U.D.C. No. 621.372.413.

corrosion-resistant metals such as nickel silver and stainless steel and have small raised portions or "lands" on the four corners of one face as shown in Fig. 2c; the rear view of the electrodes is shown in Fig. 2e. These lands are intended to clamp the crystal (Fig. 2d) in the corners, while leaving an air gap of the order of 0·001 in between the faces of the crystal and the major portion of the electrodes.

Electrical connection has to be made from the two electrodes to the pins protruding from the holder. In the case of the sheet metal electrodes this is done by metallic contact with the aid of springs. For the deposited electrode type, either springs clipped on to the corners of the crystal or wires soldered direct to the face of the crystal are used, these wires or springs also acting as mechanical supports for the sandwich.

2.2. *Electrical Equivalence*

The basic property of the quartz crystal which makes it of interest to radio engineers is the phenomenon of piezoelectricity. This is the

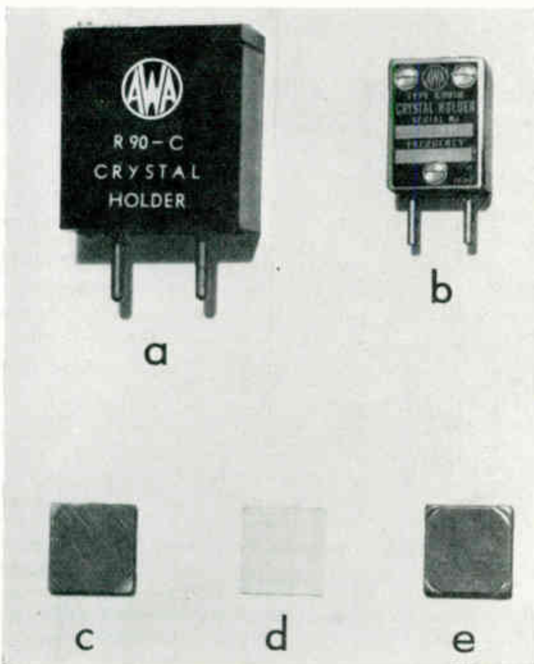

Fig. 2.—Typical bakelite moulded crystal holders, (a) and (b), together with metal electrodes (c), (e) and crystal plate (d).

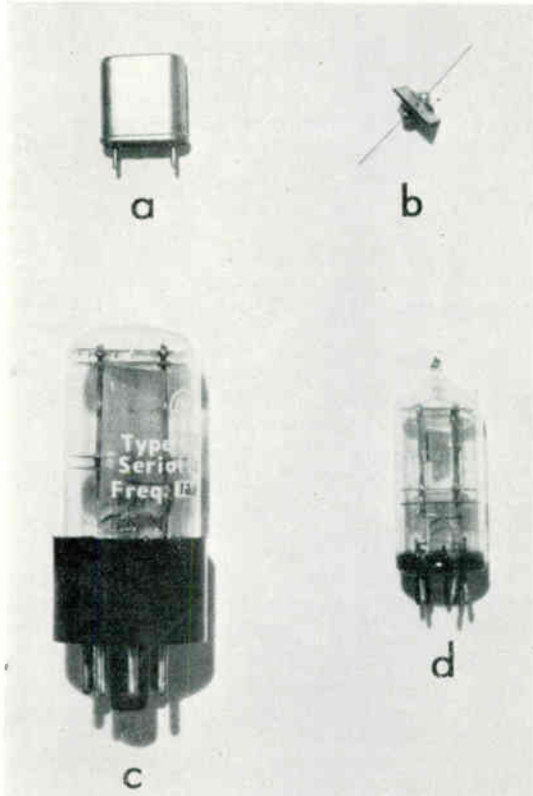

Fig. 3.—Typical sealed crystal holders and crystals. (a) Metal can type (type D); (b) Gold sputtered crystal with wired connections; (c) and (d) GT and miniature valve envelope type holders.

property whereby a stress applied to the two electrodes of the sandwich, thus causing the crystal to undergo a strain, produces electric charges at the electrodes. These charges are proportional to the stress and disappear when the stress is removed.

Strictly speaking it is the converse of this phenomenon which is employed to obtain precise control of frequency. When the crystal is connected with a suitable amplifier circuit in which energy is fed back from output to input, electrical oscillations are produced having a frequency determined almost entirely by the mechanical properties of the crystal.

In the vicinity of the frequency of mechanical resonance, the crystal can be represented by the electrical network of Fig. 4a, where C_0 is the static capacitance and L_1, C_1 and R_1 represent the motional impedance of the crystal.[1,2] For high-frequency crystals L_1 is expressed in henries and C_1 in fractions of a picofarad. C_0 varies from 5 to 35 pF depending on the type of mounting, the cut and the frequency of the crystal. The equivalent circuit Q is of the order of 30,000 or higher, giving values for R_1 in the range 20 to 300 Ω.

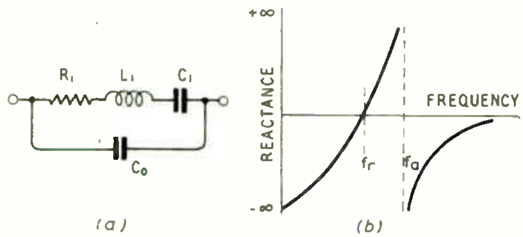

Fig. 4.—(a) An equivalent electrical circuit of a quartz crystal; (b) the reactance-frequency curve, neglecting dissipation.

The reactance-frequency curve for the electrical network, assuming R_1 to be negligible, is shown in Fig. 4b. Resonance occurs at a frequency f_r, which depends on the values of L_1 and C_1, and antiresonance occurs at a frequency f_a, which depends on the values of L_1, C_1 and C_0. Thus

$$f_r = \frac{1}{2\pi\sqrt{L_1C_1}} \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

$$f_a = \frac{1}{2\pi\sqrt{L_1 \cdot \frac{C_1C_0}{C_1+C_0}}} \quad \ldots\ldots\ldots (2)$$

and $$\frac{f_a}{f_r} = \sqrt{\frac{C_1+C_0}{C_0}} \simeq 1 + \frac{C_1}{2C_0} \quad \ldots\ldots (3)$$

The ratio of $C_1/2C_0$ is the order of 1/2000 for crystals mounted between sheet metal electrodes and 1/400 for crystals mounted between deposited electrodes. Substituting these ratios in the above equation it is found that

$$\frac{f_a - f_r}{f_r} \simeq 0{\cdot}1 \text{ per cent.} \quad \ldots\ldots\ldots (4)$$

This means that in the very narrow range of frequency $f_a - f_r$, the reactance of the crystal changes from zero to a very large positive value. It is this rapid change in reactance which accounts for the stabilizing effect of the crystal, for oscillations can be maintained only for positive or zero values of reactance.

So far it has been assumed that the crystal has only one mechanical resonance. Unfortunately for the manufacturer, this can occur only if the frequency-determining dimension is large in comparison with all other dimensions. In high-frequency crystals this is not possible, and hence the crystal is a complex vibrating system. It is the manufacturer's job to convert it to a simple vibrating system for a specified set of conditions.

The presence of more than one resonance can affect the performance of the major or desired resonance in varying degrees. In the worst case, it can cause an actual jump from one resonant frequency to another when slight changes are made in either the external circuit or the ambient temperature. At best, the effects are so small that they can be detected only by very careful checking of the crystal. Some illustrations of these will be given in a later section of this paper.

2.3. *Frequency*

The frequency of most types of crystals is primarily determined by one of the physical dimensions of the actual crystal. This is expressed mathematically by the equation

$$f = K/t \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

where K is a constant for the particular cut of crystal. In the range of frequencies considered in this paper, t is the thickness of the crystal.

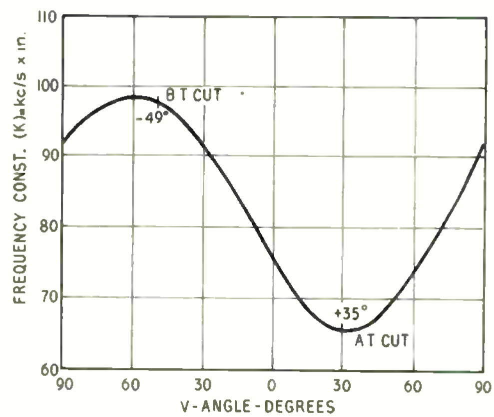

Fig. 5.—Variations of frequency constant (K) with angle of rotation (V) of "oriented-Y-cut" crystals.

Figure 5 shows the variation of K as the angle of orientation to the Y axis of the mother crystal is changed. This curve is for a crystal whose edge dimensions are very much (at least 40 times) greater than the thickness.

Two common types of cut used for high-frequency crystals, namely the AT and BT cuts,[3] are marked on Fig. 5. The slope of the curve at these points is a measure of the rate of change of *K*. For an AT-cut crystal it is 0·4 per cent. and for a BT-cut 0·25 per cent. per degree in orientation. This change is relatively small when, as is indicated later in this paper, the accuracy of determining this angle is of the order of one quarter degree.

As the thickness dimension increases, that is as the frequency decreases, and the edge dimensions become only 20 or 10 times greater than the thickness, then the simple formula is true only for limited changes in *t* and *f*. This is due to the increasing strength of mechanical coupling to other modes of oscillation present in the crystal. Fig. 6 shows the variation of *K* for a Y-cut plate of differing ratios of edge dimensions to thickness.[4] It can be seen that for low ratios there are sharp variations in *K*, the size of the variations decreasing as this ratio increases.

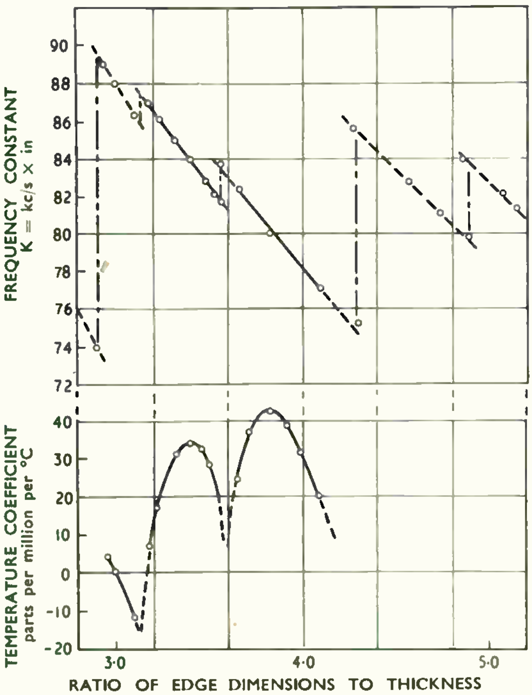

Fig. 6.—The temperature coefficient and frequency constant of a thick square Y-cut plate.

Such low ratios are actually met in practice. For instance, a 1-in square 300-kc/s AT-cut crystal has a ratio of 5, and a 1,500-kc/s AT-cut crystal mounted in a type D holder has a ratio of 12.

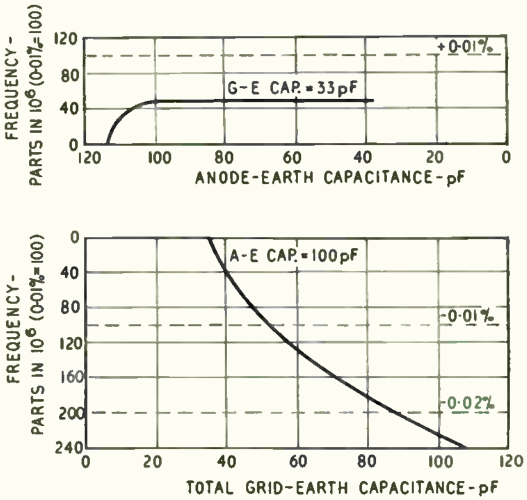

Fig. 7.—Curves showing the change in frequency of a crystal with change in circuit capacitances, for grid-cathode connection of a 3450-kc/s crystal in type R90C holder.

In crystal oscillators which use the parallel resonant frequency of the crystal, the component values of the circuit external to the crystal have some effect on the frequency of the oscillator. For average oscillator circuits and the commercial tolerances of some ten years ago it was possible to neglect this factor. But nowadays, when the most common tolerance is 0·01 per cent. and in many cases 0·005 per cent. over wide temperature ranges, it can no longer be neglected.

Figures 7 and 8 give some idea of the amount of frequency change that can take place by varying certain component values. It is obvious that frequency changes of the order of 0·005 per cent. can occur only too readily in circuits which at first glance appear to be similar. It is equally obvious that for tolerances of 0·01 per cent. or better it is necessary to have a detailed knowledge of the circuit in which the crystal is to be used before finally adjusting it in manufacture.

In past years this problem was overcome by supplying the manufacturer with a sample of the actual oscillator in which finally the crystals were to be adjusted. This method had two major objections. The sample oscillator had to be available whenever a new crystal was required, which could occur at any time during the life of the equipment; also the crystal was likely to be out of tolerance if used in some other piece of equipment. These objections are being overcome by the use of standard capacitance values to be placed in parallel with the crystals during final adjustment.

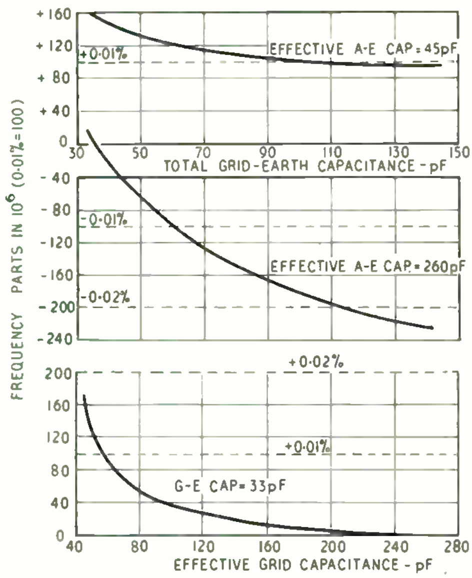

Fig. 8.—Curves showing the change in frequency of a crystal with change in circuit capacitances for anode-grid connection of a 3450-kc/s crystal in type R90C holder.

Figure 9 shows the equivalent electrical circuit of a parallel resonant crystal oscillator. As before, the two branches with L_1, C_1 and R_1 in series, paralleled by C_0 represent the actual crystal. The branches X_1 and r represent the remainder of the oscillator circuit. It has already been stated that at the frequency of oscillation, the crystal is really an inductance with a very high Q. The conditions for oscillation are that both the total reactance and the total resistance in the circuit must be zero. Hence the remainder of the circuit other than the crystal must be effectively a capacitor (say C_t) in parallel with a negative resistance. It is this value of C_t which determines the final frequency of the crystal oscillator, and if several circuits have the same value of C_t, any given crystal will have the same frequency in each circuit. It is common practice to-day to design the crystal oscillator circuit for the crystal to "see" a capacitance of a standard value. Two values of capacitance which seem to be generally accepted as standards are 30 pF and 20 pF.

2.4. *Frequency Stability*

The frequency stability of a crystal oscillator depends on three factors:—

(*a*) The frequency–temperature coefficient of the crystal.

(*b*) The ageing of the crystal.

(*c*) Variations in the circuit external to the crystal.

2.4.1. Frequency–Temperature Coefficient

The frequency–temperature coefficient of a crystal is primarily determined by the orientation of the crystal relative to the crystallographic axes of the mother crystal. Fig. 10 shows the frequency–temperature coefficient for thickness mode crystals rotated about an X axis.[4] There are two angles of rotation for which the coefficient is zero. Crystals cut at these two angles are called AT and BT cuts respectively.

From Fig. 10 it would appear that a variation of 12 minutes of angle from the 35-degree cut and of 30 minutes from the 49-degree cut would cause a change of the coefficient from zero to one part per million per degree centigrade. This is approximately correct, but actually the frequency–temperature curves for these two types of crystals are not linear.

Figure 11 shows the curves for AT and BT-cut crystals. It is seen that both curves have points

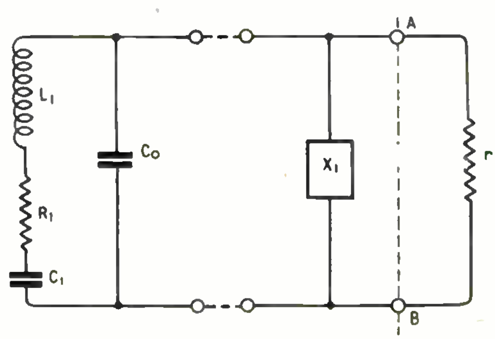

Fig. 9.—Electrical equivalent of crystal and oscillator circuit.

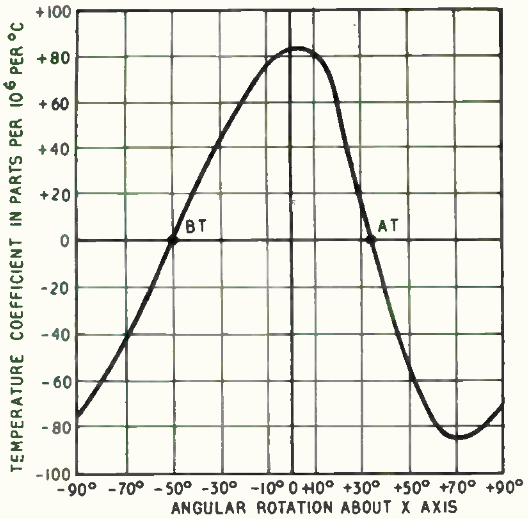

Fig. 10.—Variation of temperature coefficient with angle of rotation of "oriented-Y-cut" crystals.

of inflexion. To produce crystals having small changes of frequency for wide ranges of temperature it is necessary to control the position of these points very closely. It is found in practice that a change of one minute of angle displaces the turnover point by about one degree centigrade.

It is of interest to note that in the AT-cut the frequency change at 50°C from the point of inflexion is approximately 25 parts per million, while for a BT-cut the same frequency change occurs only 20°C from the point of inflexion. This change sets the absolute minimum tolerance for a crystal oscillator designed to work over a wide temperature range, without temperature control of the crystal. For instance, the minimum frequency change for a 100°C range (say −40° to +60°C) is 25 parts per million, which would just be covered by a tolerance of 0·0013 per cent. Also it must be remembered that this tolerance allows for no angular variation during manufacture, that it assumes that the blank can be adjusted precisely to specified frequency and that the effective capacity C_t of the remainder of the oscillator circuit will be unchanged. The accuracy of cutting crystals is of the order of 10 to 20 minutes of arc.

These curves of frequency change with temperature are subject to modification in practice by the presence of other resonances in the crystal. The lower curve in Fig. 6 shows the variation of average temperature coefficient with differing ratios of edge dimension to thickness. The variations are rather large.

Figure 12 (overleaf) shows typical curves of the frequency change with temperature of two crystals in various stages of manufacture. It is seen that as the crystal approaches more nearly to a simple vibrating system (one resonance only) the frequency change with temperature approaches the curve of Fig. 11. As stated in the section on frequency, the lower the ratio of edge dimensions to thickness the more difficult it is to make the crystal a simple vibrating system.

2.4.2. Ageing of Crystals

The thickness of a high-frequency crystal plate is of the order of 6 to 50 thousandths of an inch. It has already been stated that the frequency of the crystal is indirectly proportional to the thickness. To change the frequency of a crystal 15 thousandths of an inch thick by 0·005 per cent, the thickness must be altered by less than 1 millionth of an inch. Such

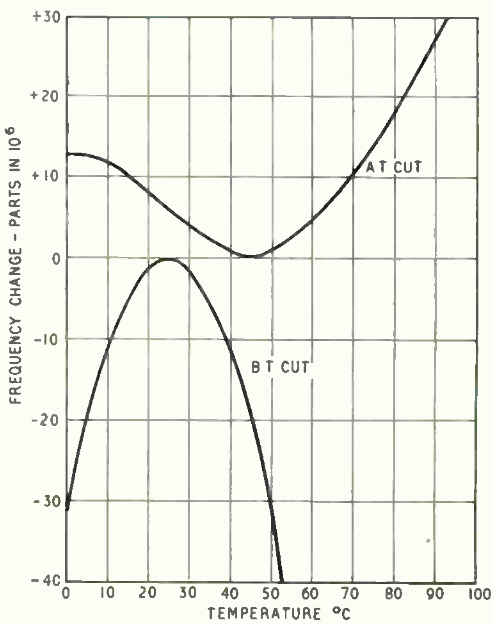

Fig. 11.—Typical frequency–temperature curves for AT and BT-cut crystals.

changes were experienced in finished crystals made prior to and during the early stages of the last war.

During the process of grinding, the surface layer of quartz is disturbed and a large number of minute cracks are developed. In the presence of moisture, weathering takes place and pieces of crystal near these cracks fall off. Thus the effective thickness of the crystal is reduced and the frequency rises.

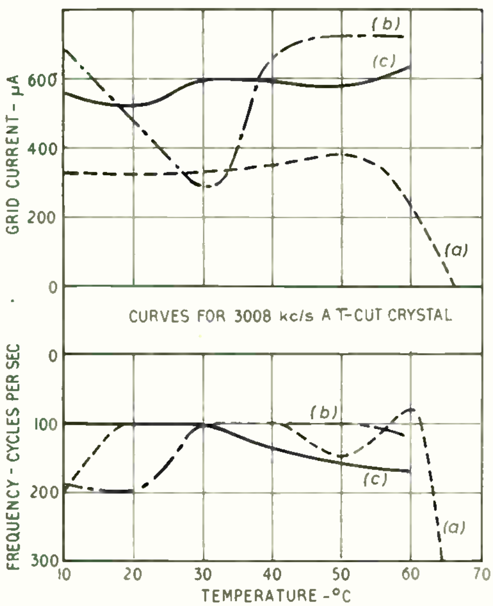

Fig. 12.—Typical curves showing change of activity and frequency with temperature at various stages of manufacture of the crystal. (a) and (b) Unfinished crystal. (c) Finished crystal.

This effect can be considerably reduced by several methods. The first is to use a very fine abrasive for the final lapping and thus produce surfaces with only very small cracks. The second is finally to etch the surface of the crystal thereby removing the disturbed layer of quartz. The third is to mount the crystal in a dry atmosphere, that is, to use a sealed holder either evacuated or filled with dry air.

The present-day method of manufacturing high-frequency crystals is to adjust the crystal finally by acid etching, making sure that the period of etching is of sufficient duration to remove completely the layer of quartz disturbed by the grinding processes. By this means the ageing is reduced to a negligible amount.

2.4.3. Circuit Variations

When dealing with frequency it was shown (Fig. 9) that the frequency of a crystal oscillator is dependent on the oscillator circuit, and that the circuit could be considered as a capacitance C_t in parallel with a negative resistance.

Figures 13 and 14 show the variation of frequency of some typical crystals with changes in C_t. It can be seen that the frequency change is less for a BT-cut than an AT-cut, and less for a gap-mounted crystal than for one mounted between deposited electrodes. For AT-cut crystals, the variation due to a change of 2 pF in input capacitance causes a frequency change of 10 to 20 parts in 10^6.

Of the above three factors affecting stability, the one most likely to cause changes is the frequency–temperature coefficient. Temperature changes in the crystal can result from both external and internal heating.

External heating can be due both to atmospheric changes and to local heating of the equipment in which the crystal is working. Careful attention during the design of the equipment to the location of the crystal relative to heat-dissipating components, such as valves, transformers and power resistors, and to ventilation, can do much to keep temperature changes down.

Internal heating of the crystal is due to the energy dissipated in the crystal itself. Although a crystal has a high Q, it still has some resistance which means that energy is dissipated in maintaining oscillations. This energy is dissipated in the form of heat. When the crystal is mounted with metal electrodes, the mass of the electrodes helps to conduct the heat away quickly and to keep the temperature down. But with crystals using plated electrodes, particularly those which are mechanically supported by the soldered wires, there is very little mass of metal to absorb and conduct the heat away. Thus the local temperature of the crystal must increase.

It should always be remembered that a crystal is a source of frequency and not power and any increase in power from a crystal oscillator is obtained at the expense of stability. With this in mind, the designer should aim to keep the voltage across the crystal to a minimum.

2.5. *Activity*

The term "activity" applied to a crystal is a rather vague one. It is probably best described as the "goodness" of a crystal as an oscillator. Until recently it has been gauged by the amount of grid current produced by the crystal in some standard oscillator circuit. This method is at best only relative—it allows the comparison of crystals for a given set of conditions. But, as the grid current is a function both of the circuit and the crystal, this measurement does not really check the crystal as an independent unit.

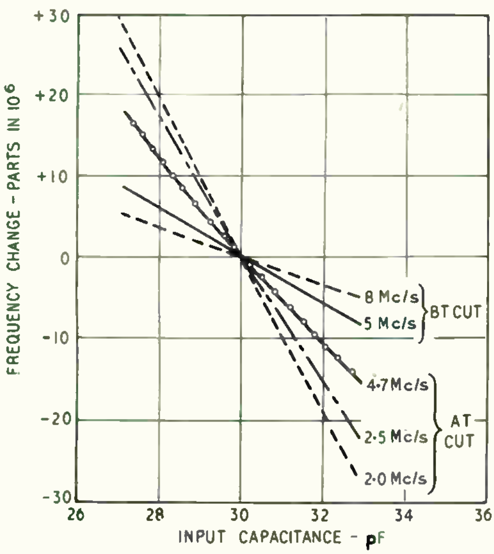

Fig. 13.—*Variation of frequency with input capacitance of oscillator circuit using type R90C holders.*

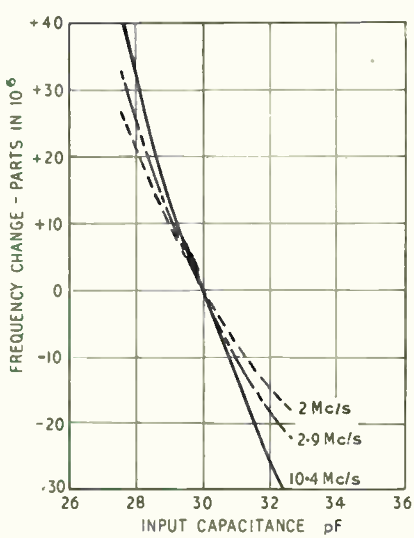

Fig. 14.—*Variation of frequency with input capacitance of oscillator circuit using type D holders.*

In the last few years a method of checking the crystal only has been developed overseas. The method consists in measuring the equivalent parallel resistance,[5] sometimes called the Performance Index,[6] of the crystal.

It was shown previously (see Fig. 9) that the crystal is effectively an inductance and the balance of the circuit a capacitance paralleled by a negative resistance. If now this capacitance be considered as part of the crystal, the impedance of the combination must be purely resistive. Thus the crystal and the capacitor form a tuned circuit with a certain dynamic resistance. In practice oscillation builds up, the magnitude of r changing until equilibrium is reached, and this is dependent on the dynamic resistance of the tuned circuit. Thus the dynamic resistance can be used as a measure of the quality of the crystal as an oscillator.

The dynamic resistance is given by the formula

$$R_{ab} = \frac{1}{R_1 \omega^2 (C_0 + C_t)^2}$$

hence the equivalent parallel resistance (e.p.r.). In this expression the only factor which is not a property of the crystal is C_t. If, however, measurements of equivalent parallel resistance are made on a crystal with two values of C_t, the e.p.r. (R_{ab}) can be calculated for any other value of C_t.

The method of measuring the equivalent parallel resistance is to compare the crystal with a tuned circuit of adjustable dynamic resistance. An oscillatory circuit is used in which the effective negative resistance generated by the valve is independent of frequency over the range of measurement. The tuned circuit has a variable element which allows accurate adjustment of the dynamic resistance by a calibrated dial without changing the frequency of oscillation. The actual measurement is made by setting the crystal oscillating, then replacing it with the adjustable tuned circuit and varying the impedance of this circuit until the same amplitude of oscillation is obtained. The e.p.r. of the crystal is then read off the setting of the calibrated dial.

The equivalent parallel resistance is not entirely independent of the amplitude of oscillation. To specify the e.p.r. fully, it is necessary to know the voltage across the crystal, when in the crystal oscillator, and measure the e.p.r. with this value of voltage. With average conditions of voltage and the usual types of vacuum tube, it is possible, however, to obtain reasonable correlation of e.p.r. with one setting of the amplitude in the test set. Fig. 15 shows the minimum limits of e.p.r. for crystals at room temperature, proposed in a recent draft of Issue 2 of Inter-Service Specification R.C.S. 271.[7]

Ideally, the activity of a crystal should not change with temperature. Owing, however, to the presence of, and coupling to, other modes of oscillation, the activity may vary greatly with temperature. One of the main problems in crystal oscillator manufacture is to maintain a smooth curve of activity over the operating temperature range. This is achieved by careful dimensioning of the crystal so that the effects of unwanted resonances are reduced to a minimum. In Fig. 12 are shown the effect of unwanted resonances on the activity. It can be seen that large changes in activity are usually accompanied by similar changes in frequency.

When specifying activity it is usual to refer to a minimum value only, no limit being placed on a maximum value. In practice, the designer of equipment must allow firstly for variations of activity over the temperature range of operation with any given crystal, and secondly for variations from one crystal to another. The sum of these two possible variations can amount to a total variation of 2 to 1 or even more.

3. Conclusion

The equipment designer requires three things of a quartz crystal. They are:—

(*a*) Size and weight commensurate with the other components in the equipment.

(*b*) Stability of frequency within certain prescribed limits for a specified range of temperature.

(*c*) Adequate output voltage for a specified set of operating conditions.

As regards (*a*), the equipment designer is entirely dependent on the crystal manufacturer, but as regard (*b*) and (*c*), the final performance of the crystal oscillator is dependent both on the quality of the quartz crystal unit and on the design of the equipment.

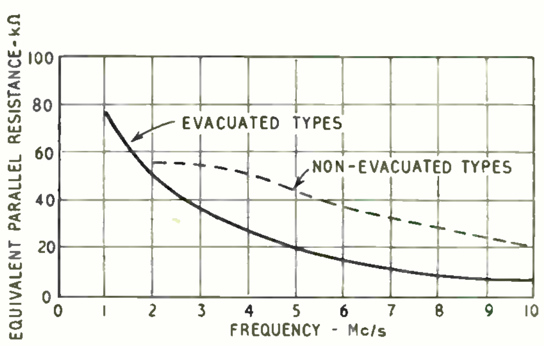

Fig. 15.—Curves showing activity limits for evacuated and non-evacuated crystals, as proposed in Ref. 7.

4. Acknowledgments

The author would like to acknowledge the assistance of his colleagues, particularly Mr. K. Smallwood, in the preparation of this paper, and to thank Amalgamated Wireless (Australasia) Limited for permission to publish it.

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5. A. J. Biggs and G. M. Wells. "The measurement of the activity of quartz oscillator crystals." *J. Instn Elect. Engrs*, **93**, Part III, 1946, p. 29.

6. C. W. Harrison. "The measurement of the performance index of quartz plates." *Bell Syst. Tech. J.*, **24**, 1945, p. 217.

7. "Quartz crystal units." Specification 271, Radio Components Standardization Sub-Committee, 1st Draft of Issue 2, Ministry of Supply, London.

GRADUATESHIP EXAMINATION—NOVEMBER 1953

SECOND PASS LIST

This list contains the results of the remaining oversea candidates not included in the list published on page 78 of the February Journal. A total of 583 candidates entered for the Examination.

Eligible for Transfer or Election to Graduateship or Higher Grade of Membership

(These candidates have now satisfied the examiners in all parts of the examination)

BHAT, Chandrashkhar Mahadeo. (S) *Poona, India.*
BRADING, Donald Hugh. (S) *Sydney, New South Wales.*

GANAPATI, Koovelimadhom Subramania. (S) *Madras.*

KAR, Bibhuti Bhuson. (S) *Calcutta.*
KHER, Sanat Kumar Madhav. (S) *Bombay.*

NARAYANAN, Nambiath. (S) *Calcutta.*

NAYAR, Vattekkat Krishnan Kutty. (S) *Deolali, India.*

RAMACHANDRA RAO, A. V. (S) *Bangalore.*
RAMAKRISHNAN, Narayana. (S) *Bombay.*

SIVASUBRAMANIAN, Kalathur Ponnappachari. (S) *Madras.*
SRINIVASAGOPALAN, C. (S) *Madras.*

WAHAB, Abdul. (S) *Karachi.*

The following candidates were successful only in the part or parts indicated

ACHUTHAN, Madras Gopalan. (S) *Delhi.* (II).
AILAWADI, Raj Kumar. (S) *Dehra Dun, India.* (II).
AJIT SINGH. *Poona, India.* (II).
ANAND, Sham Lal. *Delhi.* (II).
ARUNACHALAM, M. P. *Madras.* (IIIb).

BANERJEE, Sunil Chandra. *Cuttack, India.* (II).
BAPAT, Yeshwant Narayana. (S) *Bombay.* (IIIb).
BHARGAVA, Uma Shankar. (S) *Delhi.* (II).
BHASIN, Chaman Lal. *Gwalior, India.* (IV).
BHATTI, Dharam Singh. (S) *Nagpur, India.* (IIIb).
BOSE, Arun Kumar. (S) *Calcutta.* (IV).
BOWLES, Mervyn Edward. *Ajax, Ontario, Canada.* (I).
BRIGGS, Richard Richardson. *H.M.S. "Ceylon".* (I).

CHATTERJEE, Bhabatosh. *Calcutta.* (II, IIIa).
CHAUHAN, Narayan Velshi. (S) *Ahmedabad, India.* (II).
CHOPRA, Janak Kumar. (S) *Delhi.* (II, IIIa).
CHORADIA, Bansilal Deepchand. (S) *Poona, India.* (I).

DESAI, Priyavadan Ratilal. (S) *Bombay.* (I, IIIa).
DHANDA, Jag Mohan Krishan. (S) *Delhi.* (IIIa).

FERNANDO, Gabriel Barbetus Serenus. (S) *Colombo.* (I, II, IIIa).

GUPTA, Madan Lal. (S) *Poona, India.* (IIIa).
GUPTA, Tara Chand. (S) *Delhi.* (II, IIIa).

HUME, Cyril Robert. *Ankara.* (I).

JAGANNATHA RAO, Baji Ramachandra. *Madras.* (IV).
JEYASINGH, Rajamoney Daniel Joshua (S) *Bangalore.* (II).
JOGINDAR SINGH. (S) *Hyderabad, India.* (II).
JOOSTEN, Johan Gerhard. (S) *Christchurch, New Zealand.* (IIIa).

KAMALAKANNAN D. (S) *Madras.* (II).
KAPALI, S. (S) *Madras.* (II).
KAPUR, Harkishan Lal. (S) *Delhi.* (II).
KHAN, Mohd Ashraf. (S) *Rawalpindi, Pakistan.* (IIIa).
KHANNA, Shyam Mohan. (S) *Lucknow, India.* (IIIb).
KRISHNA MURTHY, Kumsi Subba Rao. (S) *Bangalore.* (II).
KULKARNI, Dattatraya Sadashiv Rao. (S) *Jodhpur, India.* (IIIa).
KUNDU, Sushyamal. *Bangalore.* (II).

LAHIR, Ram Lubbaya. (S) *Jullundur, India.* (I, II, IIIa).

MADAN LAL. (S) *Delhi.* (IIIb).
MAGO, H. K. Parshad. (S) *Delhi.* (II).
MALHOTRA, Hakumat Rai. (S) *Delhi.* (IIIa).
MALHOTRA, Jagmohanlal Bahri. (S) *Amritsar, India.* (IV).
MEHAR SINGH. (S) *Delhi.* (IIIa).
MITRA, Satish Chandra. (S) *Midnapore, West Bengal.* (IIIa).
MOHAN SINGH SAWHNEY. (S) *Delhi.* (I, II, IIIa).

MOHINDRA, Surendra Parkash. (S) *Dehra Dun, India.* (IIIa).
MOORE, Grahame Franklin. (S) *Hurlstone Park, New South Wales.* (II).
MUNIR, Mohammad. (S) *Multan, Pakistan.* (II).

NANDY, Sachindra Nath. *Sahagunj, West Bengal.* (II, IIIa).
NARASIMHACHAR, Mandayam Kannappan. (S) *Bangalore.* (II).
NARAYANAN, C. R. (S) *Jaipur, India.* (I, II).
NUNES, Edward Vincent. (S) *Bombay.* (II)

OAK, Arvind Narhan. (S) *Sholapur, Bombay State.* (IIIb).

PEREIRA, Anton Xavier. (S) *Colombo.* (II).
PINTO, Cyprian. *Delhi.* (II).

RAGHAVAN, Narayan. (S) *Bangalore.* (II).
RAMACHANDRA MURTY, B. (S) *Vizayawada, India.* (II).
RAMACHANDRAN, Gopalswamy. (S) *Bombay.* (IIIb).
REDDY, Anam Rajendra Prasad. (S) *Bangalore.* (II, IIIa).
REGE, Damodar Balvant. (S) *Bombay.* (II).
ROY, Prabir Chandra. (S) *Bombay.* (II).

SAHNI, Indar Singh. (S) *Delhi.* (IIIa).
SAIGAL, Raj Kumar. (S) *Agra, India.* (II).
SAMUEL, Victor Bertie. (S) *Rewa, India.* (II).
SANKARANAYANAN, S. *Bangalore.* (I).
SAPRU, Kanhaiya Lal. (S) *Delhi.* (II).
SARBJEET SINGH. *Delhi.* (I).
SARNA, Harbans Singh. *Lucknow, India.* (II).
SESHADRI, Jagannathan. (S) *Madras.* (II).
SEYMOUR, Bernard. (S) *Perth, West Australia.* (I, II, IIIa, IIIb).
SHARMA, Virendra Pal. (S) *Lucknow, India.* (IIIa).
SHUA-UD-DIN. (S) *Abottabad, Pakistan.* (II).
SINGH, Rameshwar Prasad. (S) *Nepal.* (IIIa).
SINGH, Satdev. *Dalhousie, India.* (IIIa).
SRINIVASAN, Ramachandran. *Bangalore.* (IIIb).
SUBRAMANIAM IYER. (S) *Bangalore.* (II).
SUBRAMANIAN, Hari Hara. (S) *Poona, India.* (IIIa).
SUKUMARAN NAIR, Patincharaevetil. (S) *Bangalore.* (I, II).

TARLOCHAN SINGH. (S) *Delhi.* (IIIa).
THOO KIM LAN. (S) *Kuala Lumpur, Malaya.* (II, IIIa).

UPADHYAY, Sisir Kumar. (S) *Singbhum, Bihar.* (II).

VAISHNAV, Pradyumna M. (S) *Rajkot, India.* (II).
VARMA, Ramesh Chandra. *Banaras, India.* (IIIa).
VENKATARAMANI, B. *Madras.* (IIIb).
VENKATESWARAN, K. (S) *Madras.* (IIIa).
VENKATRAMAN, Anthiyur Raju. (S) *Bangalore.* (I).
VERMA, Krishan Kumar. (S) *Delhi.* (II, IIIa).

WALLACE, Reginald Antony. (S) *Bangalore.* (I).

(S) denotes a Registered Student.

APPLICANTS FOR MEMBERSHIP

New proposals were considered by the Membership Committee at a meeting held on February 23rd, 1954, as follows: 20 proposals for direct election to Graduateship or higher grade of membership and 19 proposals for transfer to Graduateship or higher grade of membership. In addition, 42 applications for Studentship registration were considered. This list also contains the names of two applicants who have subsequently agreed to accept lower grades than that for which they originally applied.

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 circulation of this list. Any objections received will be submitted to the next meeting of the Council, with whom the final decision rests.

Direct Election to Full Member

EISLER, Paul, Dr. Ing. *London, N.W.2.*
FOSTER, Horace George, B.Sc.(Eng.), M.Sc.(Eng.) *Surbiton, Surrey.*

Transfer from Associate Member to Full Member

PATCHETT, Gerald Norman, Ph.D., B.Sc. *Bradford, Yorks.*

Direct Election to Associate Member

GRODSZINSKY, Ernst Juergen, B.Sc. *London, N.6.*
SARLL, Flt. Lt. Stanley William. *Saffron Walden, Essex.*
SEARLE, Eric Henry. *Bristol.*
SMITH, David Heseltine, B.Sc.(Eng.). *Lagos, Nigeria.*
STACEY, Edward, B.Sc.(Eng.). *Kuala Lumpur, Malaya.*

Transfer from Associate to Associate Member

HABIBULLAH, Capt. Mohamed, M.A., B.Sc. *Rawalpindi, Pakistan.*

Transfer from Graduate to Associate Member

MULLICK, Jatinder Rai. *Secunderabad, India.*
SIVARAMAKRISHNAN, Lt. K. S., B.E. *Bombay.*

Direct Election to Associate

BARNSHAW, Herbert, B.Sc. *Manchester.*
CARTER, Norman Arthur. *Romford, Essex.*
LEPPARD, Flt. Lt. Ronald William. *Saffron Walden, Essex.*
STANTON, Kenneth William. *London, E.7.*

Transfer from Student to Associate

NEWMAN, Henry John Sydney. *Ilford, Essex.*

Direct Election to Graduate

BHARMA, Flg. Off. Naresh Chandra, B.Sc., B.E.(Hons.). *New Delhi.*
HAMBLETON, James *Consett, Co. Durham.*
ORMISTON, Peter Thomas. *Morden, Surrey.*
RAO, Flg. Off. K. Ramachandra. *London, W.1.*
SHARMA, Flg. Off. Amar Nath, B.Sc.(Eng.). *Bombay.*
SPENCER, John Roger. *West Wickham, Kent.*

Transfer from Student to Graduate

CARR, Eric. *Shepperton, Middlesex.*
DIX, Dennis Lee. *Ruislip, Middlesex.*
DOREY, Cecil Frank. *Kingston, Dorset.*
ELLIS, Alfred Brian Edwin. *Londonderry, Northern Ireland.*
JALALUDDIN, Capt. Mohammed, B.Sc.(Eng.). *Karachi.*
LEE, Kenneth Pembroke. *Leeds.*
LOB, Gideon Kurt. *Ramataim, Israel.*
LOGIADIS, Minas. *Heraklion, Crete.*
ROBERTS, Stanley John. *Welling, Kent.*
SCRUSE, Stanley Warren. *London, N.13.*
SUBBARAO, Bommakanti Siva, M.Sc. *Rajkot, India.*
VASWANI, Herkishen Bulchand. *Bombay.*

Studentship Registrations

ALLISON, David Andrew. *Baden Sollingen, Germany.*
BHATNAGER, Chandra Mohan. *Lucknow, India.*
BROWNING, Robert. *Wells, Somerset.*
BUCKLEY, Alfred Eric. *Watchet, Somerset.*
BUNTING, Derek Henry Stanley. *Nairobi, Kenya.*
CHAUDHRY, Mohammad Ashraf. *Lahore, Pakistan.*
CLEAVE, John Percival, B.Sc. *Greenford, Middlesex.*
EVANS, Christopher David Ian. *Loughborough, Leics.*
GUGLEVYCH, Volodymyr. *London, S.E.5.*
HAJISTATHI, Pavlos P. *London, W.4.*
HOLMES, Ronald James. *New Malden, Surrey.*
KACZMARSKI, Wieslaw. *London, S.W.12.*
MCGINNES, Martin Screen. *Hamilton, Lanarkshire.*
MADHAVA RAO, Kancharla, B.Sc. *Madras.*
MAHAJAN, Vaman Lahu, B.Sc. *Poona, India.*
MALLIKARJUNA RAO, Viswatmula, B.Sc. *Madras.*
MARWAHA, Prem Parkash, B.Sc.(Hons.), M.Sc. *Delhi.*
MASUD BUTT, Manzur-ul-Haq, B.A., B.Sc. *Lyallpur, Pakistan.*
MATAI NARAIN, B.Sc. *Kanpur, India.*
MISSER, Ghanshyam K. *Porbandar. Saurashtra, India.*
MISHRA, Shiv Kumar, B.A. *Kanpur, India.*
MUNROE, Duke Gray. *London, S.W.17.*
MUTHANNA, Muruvanda P., *Mysore, India.*
NAYYAR, Surendar Kumar. *New Delhi.*
PETTITT, Brian Ernest, B.E. *Wolverhampton.*
ROY, George. *Howrah, West Bengal.*
SATYANARAYANA MURTY, Aylavajhala, M.Sc. *Secunderabad, India.*
SHORT, Allan. *Oakington, Cambridgeshire.*
SPILLER, Richard Henry. *Kingston, Jamaica.*
SPROSTON, Norman. *Crewe, Cheshire.*
STHALEKAR, Prabhakar Dattatraya. *Bombay.*
SUBRAMONYAN, S. Harihara, B.Sc. *Orissa, India.*
UNDERWOOD, Peter Edward, B.Sc. *Southport, Lancashire.*
VAIDIYANATHAN, Ramaswamy, B.Sc. *Madras.*
VIRICK, Harcharan Singh. *Calcutta.*
WADHWA, Captain Ram Swaroop, *Mhow, India.*
WARIN, John William. *Lydd, Kent.*
WHITE, William Michael Patrick. *B.A.O.R.*
WILLS, Alfred. *Rushden, Northants.*
WINCHCOMBE, Thomas. *Devizes, Wiltshire.*
ZAIDI, Syed Wasi Ahmad. *Karachi.*