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MINISTRY OF SUPPLY

AERONAUTICAL RESEARCH COUNCIL
REPORTS AND MEMORANDA

Electronics Applied to the Measurement of Physical Quantities

By

G. E. BENNETT, B.SC., PH.D., F.INST.P.
G. R. RICHARDS, B.SC., PH.D., A.INST.P.
and
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Summary.—The report describes the application of electromechanical and electronic principles to the design of instruments for the measurement of physical quantities such as movement, strain, pressure, acceleration, and vibratory motion, with particular reference to the special requirements of aeronautical engineering. The dynamic characteristics of pick-ups are considered, and sub-divided on an electrical basis into electromagnetic, capacitance and resistance types, a detailed description of each type being given. This is illustrated by an historical survey of their development, and by reference to a number of various recent designs and their characteristics. Piezoelectric, magnetostrictive, photoelectric, hot-wire, vibrating wire, and vacuum tube pick-ups are also considered briefly, and reference is made to calibrating devices and techniques.

An account is given of the circuits used for the conversion of the electrical variation produced in each type of pick-up into a corresponding voltage or current, particular mention being made of bridge circuits and resonance circuit methods. The special requirements of amplifiers, and the best basic circuits for satisfying them, are considered and illustrated by detailed reference to a number of particular amplifier designs; in particular, direct-coupled and carrier amplifiers are considered.

The requirements of recording equipment and the various recording methods are discussed, and a detailed account given of photographic recording and various oscillograph cameras, their optical arrangements, components and timing devices. Single and multi-channel recording equipments are considered with a brief survey of existing literature and more detailed reference to new developments of single-channel equipments designed for specific purposes, and four-, six- and twelve-channel general purpose equipments using either cathode-ray tubes or recording moving-coil galvanometers.

Finally, the application of the techniques and instruments to typical measurements undertaken since 1940 are described in order to illustrate the type of work which may be undertaken by such methods and the form and nature of the results obtained.

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1. *Introduction*.—The special considerations governing research and development work in aeronautical engineering and the present trend of development have demonstrated, perhaps more than in any other branch of engineering, the limitations of the more conventional non-electrical methods for the measurement of physical quantities, and established the possibilities and, in some cases, superiority of electrical and electronic methods. Because of the comparative ease of providing dynamic response and remote and multi-channel recording facilities with the the latter, they are particularly applicable to aircraft. A dynamic response is essential in view of the inherent flexibility and lightness of aircraft parts, and to the existence of several potent sources of both periodic and transient forces, such as the high-powered engines, propellers and aerodynamic forces. The measurement of aircraft vibration, for instance, is nowadays important owing to the increasing speed and higher design ratios, which have tended to bring the natural frequencies and the disturbing forces due to the rotating and reciprocating parts into the same frequency range, thus making resonant phenomena and failure through fatigue a practical possibility.

The conditions under which measurements on aircraft and their components have to be taken in the structural laboratory, wind tunnel, field and in flight and the information required demand the following general requirements of the measuring equipment :—

(i) *Stability and reliability*. It is essential that the instruments be reliable, that they maintain their calibration and accuracy under operating conditions and that their accuracy under these conditions be known.

(ii) *Immunity from outside disturbances*, *e.g.*, large and rapid changes in temperature and vibration, sometimes of extreme severity, may be present. Atmospheric conditions cannot be controlled, and the time for making the tests cannot always be selected with regard to the most favourable conditions.

(iii) *Compactness and lightness*.—There are often severe space restrictions and it is necessary to minimise aerodynamic forces if the measuring device is mounted externally in flight. The weight must be such that it will not affect the characteristics of the light members on which the instrument is mounted.

In addition, a desirable, if not essential, feature is

(iv) Facility for remote recording,
and in a large number of cases, to varying degrees.

(v) Dynamic response.

The last three requirements can in general best, and in many cases, only be satisfied by electrical and electronic systems and even though, as is often the case, they are less stable and reliable and less immune from outside disturbances than their mechanical or hydraulic counterparts, their use must be resorted to. It must be emphasised that in stability, absolute accuracy, robustness and simplicity, mechanical systems often surpass electrical systems and the user must correlate the two to produce the most desirable combination possible.

The magnitudes in general measured by the aeronautical engineer include strain, force, fluid pressure, movement, both under static and dynamic conditions, torque and torsional vibration, and vibratory motion, involving frequency, amplitude, velocity and acceleration. More than one of these and spurious effects may be present at the point of measurement and the measuring system must be capable of distinguishing between them. Thermal expansion, for instance, must not affect a measurement of strain produced by applied force.

Movements may be measured with virtually the same devices used for strain, although usually the magnitudes being measured will be greater. Force can be measured in terms of the strain produced in a given test specimen of known characteristics. Measurement of pressure, or force per unit area, is usually accomplished by measuring the displacement of a diaphragm or bellows and any device for measuring small movements can be applied. Measurements of vibration may be applied to either of two types of investigation ; they may be made on aircraft in flight in order to correct or improve their performance, or they may be made upon structures caused to vibrate by applied external forces in order to determine the dynamic characteristics of these structures.

The three parameters of an electrical circuit which affect the flow of current through that circuit are capacitance, inductance and resistance. A change in any one of these will produce a change in the magnitude, phase or frequency of the current flowing through that or some associated circuit. Such changes, if they can be produced by mechanical effects, may therefore be used as means of measuring such effects and all three have been used as a basis for electrical instruments for the measurement of mechanical magnitudes. The part of such an instrument which is installed at the point of measurement and which serves to convert the mechanical effect into a change in an electrical system is termed the pick-up unit. The capacitance-type pick-up is one of the earliest forms and is now chiefly used for the measurement of fluid pressure. The inductance type has a wide application, chiefly to the measurement of movement, pressure and acceleration. Pick-ups of the variable-resistance types, which can be extremely small and light and can have wide frequency response, probably find the most varied applications.

There are also in use instruments whose pick-ups employ other electrical or quasi-electrical principles such as piezoelectricity, magnetostriction and photoelectricity. Accelerations, velocities and displacements of continuously vibrating parts are in general measured by devices employing generator-type electromagnetic pick-ups.

In all such systems, with very few exceptions, it is important to notice that some movement is involved. If the required measurement is one of pressure, load, velocity or acceleration, some mechanical element must be introduced to experience a strain or movement proportional to the magnitude being measured. This results in specific requirements for pick-ups for pressure, vibration, acceleration, etc., and makes the mechanical considerations of these pick-ups as important as the electrical considerations.

In addition to the pick-up unit defined above, a complete instrument of the type described in the present report will in general consist of an associated circuit, for conversion of the particular electrical parameter used into a corresponding voltage, an appropriate amplifier and an indicator or recorder for displaying or preserving the measured data. For static measurements, the auxiliary equipment may not be complex, but if the measurements are of dynamic effects the size and complexity will in general be greatly increased. Yet, in aeronautical engineering, dynamic, or combinations of dynamic and static, or slowly varying measurements are often required and continuous recording is the only means by which the necessary data can be obtained. Even if the tests are essentially static, but are made at many points of a complex structure in a short period of time, it may be necessary or advantageous to provide some recording facilities.

To cover the whole field of measurement in aircraft research and development it is necessary that the instruments possess a very wide frequency response, which may extend from static conditions to frequencies far above the audible range. It has been found that, particularly for flight equipment where size, weight and operation under adverse temperature conditions and discomfort, are major considerations, it is more satisfactory and economical to sub-divide the general frequency response requirements into four categories :—

(i) Static conditions.

(ii) Static conditions to 100 c.p.s.

(iii) 2 or 3 to 1000 c.p.s.

(iv) 20 to 50,000 c.p.s. or higher.

In the case of equipment for use in ground tests, however, it is generally possible to design one instrument to cover the complete frequency range.

The above general considerations on instruments using electrical and electronic techniques for the measurement of physical quantities in aeronautical engineering is intended to serve as an introduction to the more detailed considerations following. It may be said that at present the systems described are in an unco-ordinated condition and that any particular technique is applicable to more than one type of measurement. The classification adopted in this report, therefore, has been based on the electrical parameters used rather than on the quantities measured and it has been considered relevant to include a section on mechanical considerations of pick-up units. A section is also included on the special requirements for auxiliary circuits and recording devices before dealing with particular instruments and their applications.

It should be pointed out that the instruments and techniques of the types described and their application in aeronautical engineering, have developed to such an extent since 1939 that only a general description can be given. References to more detailed considerations of some of the subjects are therefore included.

2. *Mechanical Considerations of Pick-up Units.*—2.1. *Introduction.*—Experience has shown that in the development and design of electronic measuring instruments the mechanical considerations governing the design of the electro-mechanical pick-up are as important, if not more important, than the electrical considerations of the complete equipment. It is frequently found that the measurements possible, with the required degree of accuracy and with a given instrument, are determined by the mechanical characteristics of the pick-up.

As stated in Section 1, in all types of pick-ups some movement is involved. If the required measurement is one of pressure, load, velocity or acceleration some mechanical element in the pick-up must experience a strain or movement proportional, over the operating range, to the magnitude being measured. The mechanical characteristics of pick-ups fall into three distinct classes :—

(i) Those, having a natural frequency considerably above the frequencies to be measured and which use the inertia effect of a mass as small as possible suspended as rigidly as possible, *e.g.*, those used for the measurement of acceleration and fluid pressures.

(ii) Those used above their natural frequency and which use the inertia effect of a mass as large as possible suspended on a spring as weak as possible, *e.g.*, seismic vibration pick-ups.

(iii) Those which do not incorporate any intentional flexibility and take up the characteristics of the particular structure to which they are attached, *e.g.*, strain units.

Typical examples of each class will be considered in their application to measurements in aeronautical engineering. In such applications it is required to record faithfully

(a) signals comprising a single-frequency sinusoidal variation or a number of sinusoidal variations of differing frequencies,

(b) signals of a transient nature,

(c) signals of types (a) or (b), or a combination of them, occurring at a number of different points simultaneously—multi-channel recording.

Owing to the complicated nature of the signals encountered in practice, it is frequently found difficult to define strictly the requirements to be satisfied for faithful recording. It is convenient and useful, however, to consider, as a first step, the response of the pick-up to sinusoidal variations. An alternative method, of particular use when dealing with transients, is to consider the response of the pick-up to a step function or a function increasing linearly with time. This response may be determined either practically, by injecting a known function, or by computation from a knowledge of the undamped natural frequency and damping factor. Once this response is determined, it may be used to deduce that of any other form of signal. The production of a suitable movement by the effect to be measured will be considered in this Section, it being assumed that the further conversion of the movement into an electrical parameter is a strictly proportional effect. The three chief requirements to be satisfied by a pick-up, are then :—

(i) At any frequency, in the operating range, the movement produced must be proportional to the effect in that range,

(ii) For a given magnitude of the effect, the movement must be independent of frequency over the specified operating frequency range,

(iii) The time delay produced must be independent of frequency over the specified operating frequency range.

2.2. *Acceleration Pick-up*.—2.2.1. *General*.—In this type of pick-up an elastically supported mass is subjected to the accelerations to be measured and its resulting movements converted into a corresponding electrical signal. Over the range of amplitude and frequencies to be measured, the motion of the mass must be strictly proportional to the impressed acceleration and, therefore, to the force acting on the mass, and be independent of frequency, *i.e.*, give no resonance effects. Such a system may be considered ideally as a system of one degree of freedom with an ideal linear spring and damping proportional to the velocity of the moving mass (viscous damping). Therefore, it may be represented by the system of Fig. 1 in which $P \sin pt$ is the sinusoidal impressed force of frequency $p/2\pi$, m is the mass supported on a spring of stiffness k, and h the damping factor, being the ratio of the damping present to the amount which would constitute critical damping ($h = c/c_0$, where c is the damping coefficient, *i.e.*, the constant of proportionality between the damping force and velocity of movement, and $c_0 = 2\sqrt{(mk)}$ is the critical damping coefficient).

The 'steady-state' amplitude x of the motion of the mass resulting from the application of the force $P \sin pt$ is then given by

$$x = b \sin (pt - \psi)$$

which is the particular integral of the general equation of motion of the system. This is the only part of the complete motion that is important, it being assumed that the motion represented by the complementary function, which is a decreasing time function, is practically damped out. The motion is thus sinusoidal of the same frequency as the exciting force but lagging behind it by the angle ψ, called the phase angle. The amplitude of motion is given by[1]

$$b = \frac{P}{k\left[\left\{1 - \left(\frac{p}{\omega}\right)^2\right\}^2 + 4h^2\left(\frac{p}{\omega}\right)^2\right]^{1/2}} \quad \ldots \quad (1)$$

where $\omega = (k/m)^{1/2} = 2\pi \times$ undamped natural frequency of the system.

The phase angle ψ is given by

$$\tan \psi = \frac{2h\,(p/\omega)}{1 - (p/\omega)^2}. \quad \ldots \quad (2)$$

There are three particular frequencies associated with this system :—

(i) The undamped natural frequency, f_u, which is the frequency of free vibration of the system in the absence of damping and is given by

$$f_u = \frac{1}{2\pi}\sqrt{\left(\frac{k}{m}\right)} = \frac{\omega}{2\pi}.$$

(ii) The damped natural frequency, f_d, which is the frequency of free vibration of the system in the presence of damping and is given by

$$f_d = f_u\,(1 - h^2)^{1/2}. \quad \ldots \quad (3)$$

(iii) The resonant frequency, f_r, which is the frequency of the impressed force at which the amplitude of motion of the mass is a maximum for a given amplitude of the impressed force. It is given by

$$f_r = f_u (1 - 2h^2)^{1/2}$$

and decreases with increase in damping.

Variation of f_d/f_u and f_r/f_u with damping for this type of system is shown in Fig. 2. In the present work, which is concerned in the majority of cases with comparatively highly damped systems, it is important not to confuse these three particular frequencies. They may be considered equal only when the damping in the system is so small as to be negligible.

2.2.2. *Response to acceleration of constant frequency.*—At a given frequency of excitation it is seen from equation (1) that the movement of the mass is proportional to the impressed force and therefore to the impressed acceleration. This remains so provided the conditions stated in section 2.2.1 are satisfied. In particular, it is not so when the damping due to constant friction (Coulomb damping) is appreciable, but is so when the damping is produced by a fluid surrounding the mass, or by electromagnetic means.

To obtain a pick-up with a linear response to accelerations of a given frequency it is further necessary to arrange that the movement produces a proportional change in the particular electrical parameter used. This will be discussed further in later sections and it will suffice to mention here that it is sometimes found necessary to combine two non-linear responses in order to produce an overall linear response, as in the case of the capacity type pressure unit.

2.2.3. *Response to accelerations of varying frequency.*—The ratio of the amplitude of motion of the mass at a particular frequency (given by equation (1)) to the deflection P/k produced by the application of a static force equal in magnitude to the amplitude of the impressed dynamic force is called the 'dynamic magnification' at that particular frequency. Curves of this ratio for a range of damping factors between 0·1 and 1·0 are reproduced in Fig. 3, the abscissæ being the ratio of impressed frequency to natural undamped frequency, sometimes called the 'discord.' These curves show that the response is independent of impressed frequency, with a certain permissible error, from zero frequency up to a certain discord whose value is determined by the damping factor. Taking a permissible error of $\pm$ 5 per cent, if the damping factor is small, say 0·1 critical or less, the response of the accelerometer may be considered independent of frequency up to 0·2 of its undamped natural frequency. To get the largest range of frequencies over which the response can be considered independent of frequency the damping factor has to be about 0·65. At this value the workable range of frequencies extends from zero up to approximately 0·8 of the undamped natural frequency. In general, to obtain this condition, damping additional to that inherent in the system, such as that given by oil or electromagnetic effects, has to be introduced.

Inherent damping in accelerometers usually varies over the approximate range of 0·01 to 0·4 times critical. It is possible to utilise this damping only and make the undamped natural frequency of the accelerometer so high that over the working range of frequencies the variation in response is negligible. (For 0·1 critical damping the undamped natural frequency, damped natural frequency and resonant frequency of the system are equal to within 1 per cent). In practice, however, three considerations make this difficult :—

(i) The movement of the mass due to a given impressed acceleration is inversely proportional to the stiffness of the system, that is to the square of the undamped natural frequency, so that if this is increased to reduce the variation in response over the working range, there is a corresponding decrease in sensitivity. This, in general, cannot be tolerated.

(ii) If the damping is not one particular value, the phase angle between the impressed force and the movement of the mass, to be described below, varies non-linearly with the frequency. In general this variation will cause distortion, time lags of different magnitudes being introduced for different frequency components in the measured accelerations.

(iii) When the damping is small any possible resonance or shock excitation of the pick-up is liable to produce mechanical damage and spurious signals.

2.2.4. *Distortion due to phase angle.*—The phase angle, or angle of lag between the impressed force and movement of the accelerometer mass, depends upon the impressed frequency and damping coefficient. It is given by equation (2) above. Curves showing variation of phase angle with discord (p/ω) for different values of damping factor (h) are given in Fig. 4. This phase angle results in a time-lag between the application of the acceleration to the pick-up and the production of the corresponding movement of the mass, the time-lag produced by a given phase angle being inversely proportional to the frequency of the acceleration. An acceleration signal consisting of a single-frequency sinusoidal variation will, therefore, be displaced along the time axis by an amount depending on its frequency and this displacement will not result in an error in the measurement unless it is required to relate the acceleration signal with another event. In the following cases, however, which are most frequently encountered in practice, the existence of this phase angle does result in an error :—

(i) When the signal, analysed into its components, consists of a number of sinusoidal variations of a number of different frequencies, fundamental and harmonics, each component is displaced along the time axis by a different amount and the composite signal recorded is therefore distorted.

(ii) When a transient signal is being recorded.

(iii) When simultaneous recording at a number of points of any type of signals, even single-frequency sine waves, is required in order to relate, with respect to time, the accelerations at these points, displacement along the time axis or distortion of the signals can occur.

While the above is generally true, there are two values of the damping factor for which phase distortion and relative displacement along the time axis can be neglected over a given frequency range. The first is that which results in a phase angle between the impressed force and resultant movement so small that it may be neglected. If, for example, damping is less than 0·1 critical the phase angle can be neglected over the working range of 0 to 0·2 times undamped natural frequency, *i.e.*, the range over which change of amplitude of motion due to a constant impressed force with frequency can be considered negligible. The second is that which results in a phase angle proportional to the frequency. Since the time lag for a given phase angle is inversely proportional to the frequency, when this condition holds the time lag will be independent of frequency and the signal, whatever its form, will merely be displaced along the time axis without distortion. The only value of damping to obtain this desired result is about 0·75 critical.

It was seen in Section 2.2.3 that, to get the largest range of frequencies over which the response to a given acceleration can be considered independent of frequency, a damping factor of 0·65 is necessary. For this value the response is independent of frequency, to within $\pm$ 5 per cent in the range zero to 0·8 times the undamped natural frequency and the phase angle is proportional to frequency within $\pm$ 5 per cent, in the frequency range 0 to 0·75 times the undamped natural frequency. It is seen, therefore, that from a consideration of errors due to both amplitude attenuation and phase angle, a damping coefficient of about 0·6 times the critical value is the most satisfactory. For this condition, both errors are less than $\pm$ 5 per cent over the frequency range zero to 0·75 times the undamped natural frequency.

2.2.5. *Sensitivity.*—On mechanical considerations only, paying no attention to the requirements of the linear conversion of movement into a corresponding electrical parameter, it is desirable that as large a movement as possible of the suspended mass be produced per unit acceleration. Taking the optimum damping coefficient as 0·6 critical and the permissible error for both amplitude attenuation and phase distortion as $\pm$ 5 per cent, the minimum undamped natural frequency required in a pick-up for use over a given range of frequencies is 1·3 times the highest frequency to be recorded.

Using the notation previously defined and d as the deflection of the mass m for an acceleration of one g, then

$$f_u = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$$

and

$$k = \frac{mg}{d}.$$

Therefore, $$f_u = \frac{1}{2\pi}\sqrt{\frac{g}{d}}.$$

From this equation the mechanical sensitivity of the acceleration pick-up may be determined. It is, of course, independent of the means utilised to convert the movement into a corresponding electrical signal. The greater the value of the damping factor (up to the optimum value of 0·6 critical) the lower can be the undamped natural frequency of the system and thus the greater the deflection sensitivity for a given working range of frequencies.

2.2.6. *Determination of the mechanical characteristics of acceleration pick-ups.*—It has been found essential, both in the development of pick-ups and in their application to actual measurements, to have a practical means of determining the range of frequencies over which the pick-up may be used. This could, of course, be done by subjecting the pick-up to known accelerations at known frequencies, and recording its output. Unfortunately, vibrating mechanisms to cover a sufficiently wide frequency range are complicated and difficult to use, and therefore it is convenient to use a method which combines measurement with the mathemetical treatment already outlined. In this method it is necessary to determine experimentally the undamped and damped natural frequencies and the damping factor.

The pick-up is fixed to a rigid base and shock-excited by tapping lightly with a resilient rod, its electrical output being recorded with its associated electrical equipment. From the resulting decay curve the damping factor h can be calculated by one of the two following methods:—

(i) Use of the formula

$$h = \log_{10}(A_0/A_n) \,/\, \sqrt{(1{\cdot}862n^2 + \log_{10} A_0/A_n)},$$

where A_0 is the first considered amplitude measured from the rest position and A_n is the amplitude of the nth succeeding swing past the rest position.

(ii) Comparison with the decay curves derived theoretically for different values of damping factor. A set of such curves are shown in Fig. 5, and from these it is seen that if the damping factor is less than 0·2 the damped natural frequency can be measured directly from the accelerometer decay curve obtained experimentally. Then, using equation (3) above, the undamped natural frequency of the system can be calculated. When the damping factor has been thus determined the amplitude-frequency response curve can be plotted from equation (1), knowledge of the undamped natural frequency of the system enabling the abscissæ to be plotted directly in terms of frequency. Phase angle at different frequencies can be calculated from equation (2) and the magnitude of both the displacement along the time axis and phase distortion determined.

If the damping factor is greater than about 0·4, its value can be obtained by method (i) or (ii) outlined above, but it is difficult to obtain the damped natural frequency from measurements on the decay curve. If possible, it is better, after determining the damping factor to reduce the damping and to obtain the new damping coefficient and damped natural frequency. From these values the undamped natural frequency can be obtained by the use of equation (3). From the value of the undamped natural frequency and original damping factor the response curve can be obtained from equation (1).

2.3. *Pressure Pick-ups.*—The above considerations apply, with the appropriate adaptation, to pick-ups for the measurement of fluid pressures, irrespective of the nature of the electrical parameter used. For the capacity-type pressure pick-up, for example, the stiffness is that of the diaphragm to which the pressure is applied and the movement is the deflection of this diaphragm. For the quartz crystal pick-up, the stiffness is that of the piston crystal system and the movement, the elongation or contraction of the crystal.

2.4. *Seismic Vibration Pick-ups.*—2.4.1. *General.*—The seismic vibration pick-up, which, when associated with its recording mechanism is a vibrograph, is in principle like the acceleration pick-up, a mass suspended on a spring with the requisite damping. Unlike the acceleration pick-up, however, in this case the natural frequency is as low as possible and the pick-up is used at frequencies above this value. It measures the displacement of the mass relative to the body of the pick-up which is rigidly attached to the structure under investigation. Therefore, it measures the absolute displacement of the vibrating body.

The system may be represented by Fig. 6 in which m, k and h have the same significance as for the acceleration pick-up ; x is the displacement of the body under investigation which is assumed to be executing a sinusoidal vibration of amplitude x, and frequency $p/2\pi$ c.p.s. It can be shown[2] that the motion of the mass relative to the vibrating body is sinusoidal, with the same frequency $p/2\pi$ as that body and with a relative amplitude given by

$$\text{Relative amplitude} = \frac{(p/\omega)^2 X}{[\{1 - (p/\omega)^2\}^2 + 4h^2 (p/\omega)^2]^{1/2}} \qquad \text{(4)}$$

where $\omega = (k/m)^{1/2} = 2\pi$ times undamped natural frequency of the system. p/ω is the ratio of the frequency of the vibrating body (the impressed frequency) to the undamped natural frequency of the system.

The phase difference between the motion of the vibrating body and that of the mass is given by

$$\tan \psi = \frac{2h(p/\omega)}{1 - (p/\omega)^2} . \qquad \text{(5)}$$

There are three particular frequencies associated with this system.

(i) The undamped natural frequency, f_u which, as for the acceleration pick-up, is given by

$$f_u = \frac{1}{2\pi}\sqrt{\frac{k}{m}} = \frac{\omega}{2\pi} .$$

(ii) The damped natural frequency, f_d which, as for the acceleration pick-up is given by

$$f_d = f_u (1 - h^2)^{1/2}. \qquad \text{(6)}$$

(iii) The resonant frequency, f_r, which in this case is given by

$$f_r = f_u (1 - 2h^2)^{-1/2}. \qquad \text{(7)}$$

Unlike that of the acceleration pick-up, the resonant frequency of a seismic vibrating pick-up increases with increase in damping as shown by the curves reproduced in Fig. 7.

2.4.2. *Response to vibration of constant frequency.*—It is seen from equation (4) that for a given damping factor and undamped natural frequency the relative amplitude of the mass is proportional to the amplitude of motion of the vibrating body at any particular frequency. To obtain a pick-up with a linear response to vibration amplitude, it is further necessary to arrange that the movement produces a proportional change in the particular electrical parameter used. A seismic vibration pick-up frequently consists of a coil suspended in the field of a permanent magnet. In this case, although the movement of the coil relative to the magnet is a linear function of the vibration amplitude, the signal generated is proportional to the velocity of the vibration and the amplitude has to be obtained by integration using an electrical integrating circuit.

2.4.3. *Response to vibration of varying frequency.*—Figs. 8, 9 show curves for the ratio of relative amplitude of mass and body of the pick-up against the ratio of the impressed frequency to the undamped natural frequency for values of the damping factor between 0·1 and 0·7. True recording of a complex vibration comprising a number of sinusoidal components of different frequencies is only made when the relative motion of the mass for a given vibration amplitude is independent of frequency. When this condition holds the mass m is stationary in the gravitational field of the earth and the recorded relative motion, therefore, is exactly the same as the absolute motion of the vibrating member in the gravitational field.

It is seen from these curves that this is practically so from some frequency above the undamped natural frequency upwards, the lower limit of frequency depending upon the value of the damping. Taking the permissible error as $\pm$ 5 per cent, as in the case of the acceleration pick-up, if the damping factor h is 0·6 the response is true at all frequencies above about 1·25 times the undamped natural frequency. If the damping is less, or greater than, 0·6 times critical, the lower limit of the frequency range is correspondingly raised. For example, if the damping is less than 0·1 critical the lower limit of frequency for which the error in response is less than $\pm$ 5 per cent is 4·5 times the undamped natural frequency. It is true that a single frequency sinusoidal vibration can be recorded accurately at lower frequencies than these limits by using a frequency correction factor but in practice, owing to the presence of harmonics, this process is difficult, if not impossible. No upper limit to the frequency range for true response is set by theoretical considerations. In practice, however, it is found that a limit is set by the degree of flexibility of the pick-up body supporting the spring-mass system and by the stresses set up in the spring tending to produce failure through fatigue.

2.4.4. *Distortion due to phase difference.*—The phase angle or angle of lead between the vibration and the corresponding movement of the seismic mass is given by equation (2) and shown in Fig. 4, as for the acceleration pick-up. As in the latter case, discussed in Section 2.2.3, distortion may be introduced by this phase difference, the relative frequencies in the case of the vibration pick-up being above the undamped natural frequency. For no distortion the phase angle must be 180 deg, the frequency at which this is attained in practice depending upon the value of the damping factor. Assuming a damping factor of 0·1 the phase error can be considered negligible at frequencies above three times the undamped natural frequency, whereas for the same damping factor the amplitude response is satisfactory at frequencies above five times the natural frequency. For a damping factor of 0·6, when the amplitude response is satisfactory down to 1·25 times the undamped natural frequency, the errors due to the phase angle will be negligible at frequencies above approximately 10 times this natural frequency. Below this value of frequency the displacement along the time axis and phase distortion are large and variable.

2.4.5. *Determination of the mechanical characteristics of seismic vibration pick-ups.*—The damping factor, resonant frequency, undamped and damped natural frequencies and frequency response curves can be obtained by the methods outlined in Section 2.2.5 for acceleration pick-ups and by the use of equations (4) to (7). In view of their low undamped natural frequencies, it is generally possible to obtain experimentally the dynamic response curves of this type of pick-up.

2.5. *Non-seismic Proximity Vibration Pick-ups.*—When it is required to measure the vibration of a body relative to a fixed point which is accessible, such as the ground, it is then unnecessary to use the seismic principle, the stationary part of the pick-up being fixed to ground and the moving part to the vibrating body. There need be no mechanical connection between the stationary and moving parts, but sometimes it is found convenient to incorporate a light spring system of a sufficiently low natural frequency. The mechanics of such a pick-up is relatively simple provided the attachment of the moving and stationary parts to the vibrating body and to the ground, respectively, are rigid enough not to introduce any extraneous resonances in the working frequency range. The stiffness and damping between the moving and fixed parts of the pick-up must be small and not sufficient to modify the dynamic characteristics of the system under test.

2.6. *Strain Units.*—Two types of strain units are in general use :—

(i) The integral unit, normally cemented over its whole area to the test specimen, and in which a stress proportional to the strain under measurement is set up.

(ii) The composite unit, in which each separate part is cemented to the test specimen, and in which no stress is set up by the applied movement.

In the first type, when the strain unit is firmly cemented it forms part of the structure under test and takes up the mechanical characteristics of that structure. The cementing must be such that it is capable of transmitting the force required to strain the unit to the same extent as the structure. There is, however, an upper limit of frequency response for the unit. Accurate information regarding this is not available but it is known that the units will operate up to the point where their length becomes comparable with the length of the corresponding stress waves in the material under test. For steel in which sound travels with an approximate velocity of $2 \cdot 10^5$ in./sec and a strain unit length 1 in. this practical upper limit is of the order of 50,000 c.p.s., when the error is 10 per cent. There is, however, no phase error up to 100,000 c.p.s.[3] These units have been successfully used up to frequencies of the order of 50,000 c.p.s. In practice the upper limit of frequency response is generally dictated not by the strain unit but by the associated electronic circuits and recording devices.

2.7. *Methods of Damping.*—2.7.1. *Coulomb damping.*—The above deductions regarding the amplitude, frequency and phase response of pick-up units have been derived assuming that the damping forces between the moving and fixed element of the unit are proportional to the velocity of relative movement. This is the simplest type of damping and it is necessary in practice to obtain as near an approximation as possible to this condition.

Damping forces which are not of this type may arise from friction between the dry sliding surfaces of the bodies in motion or from internal friction due to the imperfect elasticity of vibrating bodies. This latter source of damping is normally small compared with the other sources and may in practice be neglected. In the case of friction between dry surfaces the Coulomb-Morin law is usually applied. The frictional force is assumed proportional to the normal pressure acting between the surfaces, the constant of proportionality being the coefficient of friction, whose value depends on the material of the bodies in contact and on the roughness of their surfaces. The resulting damping force is then independent of the relative velocity of the bodies when they are in motion, if the surfaces are reasonably smooth. When the surfaces are rough the force diminishes with increase in velocity. It is also found that the friction force required to start the motion is greater than that required to maintain it and, if the friction is large, this may introduce serious errors in the response of a pick-up.

If the Coulomb friction is appreciable and variable it will seriously modify the response of the pick-up to an impressed wave form[4,5]. In some cases momentary ' sticking ' of the moving element may result. Wherever possible it is advisable to keep this Coulomb friction down to a minimum, and, where this is not possible, to ensure some degree of constancy by keeping in constant rotation parts which move relative to one another. This reduces the possibility of sticking at the commencement of motion, before the forces involved are sufficient to overcome static friction.

2.7.2. *Velocity damping.*—The required degree of velocity damping, in which the force is proportional to the relative velocity of the moving bodies, may be introduced by any one of, or a combination of, the following methods :—

(i) Friction between lubricated surfaces.

(ii) Fluid resistance.

(iii) Electromagnetic.

In the case of friction between lubricated surfaces the friction force depends upon the viscosity of the lubricant and on the velocity of relative motion and is independent of the materials of the moving bodies. For perfectly lubricated surfaces in which there exists a continuous lubricating film between the sliding surfaces, it can be assumed that friction forces are proportional both to the viscosity of the lubricant and to the relative velocity. In practice, however, it is found that this ideal condition is far from attained and the damping tends to develop into Coulomb damping.

Friction forces proportional to velocity are also obtained if a body is moving with a low velocity in a viscous fluid or if the moving body causes fluid to be forced through narrow passages, as in the case of dashpots. This latter method produces a small degree of damping in the capacity-type pressure pick-up to be described later, air being forced out of the pressure capsule by deflection of the actuating diaphragm. In the case of bodies moving at higher velocities in a fluid, however, the damping force is not proportional to velocity, and to a first approximation may be assumed proportional to the square of the velocity. This type of damping, introduced by arranging for the body to move in a liquid, is widely used in both vibration and acceleration pick-ups.

The principal requirements for oil for damping purposes are that it shall not evaporate quickly, shall not have any corrosive action on metals, shall be a good electrical insulator, and that its viscosity shall not change appreciably with temperature. For pick-ups for use in aircraft, fluid damping suffers from the serious disadvantage that the viscosity of the operating fluid varies greatly with temperature. Even in the case of the relatively low temperature coefficient of viscosity oils, such as the organo-silicon types, a change of a few degrees in temperature will change the value of the viscosity by as much as 100 per cent[6].

Electromagnetic methods are also used extensively for introducing damping into pick-up units. Use is made of the fact that movement of a conductor in a magnetic field produces eddy currents in it, the magnitude of which is proportional to the velocity of the conductor. A force which is always in the direction opposing the motion, and which is proportional to the velocity of the conductor, exists between these currents and the magnetic field. The magnitude of the damping produced in this way depends upon the strength of the magnetic field, specific resistance of the conductor and its dimensions and by suitable choice of these parameters the damping coefficient for a given pick-up can be made any desired value. The method of introducing eddy current damping into a pick-up depends upon the construction of the unit. For example, if the pick-up consists of a coil operating in a magnetic field, then the coil former itself can be made of a suitable material, such as copper or aluminium, for the production of eddy currents. Eddy current damping is in general more difficult to incorporate into a pick-up design, particularly if the pick-up does not already make use of a magnetic field. It is, however, far superior to fluid damping, being far less susceptible to temperature changes, more controllable and adjustable and more stable.

Velocity damping may also be introduced electrically into a pick-up incorporating a moving-coil system in a magnetic field by utilising the back e.m.f. in the coil, the required degree of damping being obtained by suitable choice of the resistance of the external circuit of the coil.

A possible method of obtaining the desired results of velocity damping in a pick-up unit without resorting to any of the above methods is to apply the negative feed-back principle. Some of the amplified output energy of the pick-up unit can be fed back in opposite phase so as to produce a force tending to oppose the original movement in the pick-up. By introducing frequency-discriminating feed-back of suitable characteristics, it would be possible to avoid the undesired resonance effects in the pick-up unit. As far as is known this method has not been widely used but it seems to offer a means of obtaining controllable damping strictly proportional to the velocity of movement of the operating element of the pick-up.

3. *Electromagnetic Pick-ups and Associated Circuits.*—3.1. *General.*—Pick-up units based on electromagnetic principles probably form the widest class applied to the measurement of physical quantities in engineering. There are several different types, with no clear demarcation line between their mode of operation, sometimes several electrical and magnetic properties varying

simultaneously and only one of them being measured. Those most frequently used for measurement in aeronautical engineering can be divided into two general classes.

(i) Variable inductance type, in which movement proportional to the physical phenomenon under measurement is converted into a measurable change in self or mutual induction. This type is generally energised by an alternating current.

(ii) Generator type, in which relative movement of a coil and magnet generates a voltage proportional to the physical phenomenon under measurement or to its time differential.

3.2. *Variable Inductance Pick-ups*.—3.2.1. *Principle*.—Pick-ups designed to give a measurable change in inductance have been applied to the indication and measurement of magnitudes of many types such as strain, pressure, acceleration, velocity and amplitude of movement. It is possible to vary the inductance in many ways but the most efficient and most widely used method is to vary the reluctance of the magnetic circuit of the inductance by altering the position of a ferromagnetic material in or near the core of the inductive coil. These are the variable air gap and the variable core types. In both cases the inductance of the associated coil is varied, this variation being converted into a corresponding voltage change in the associated circuit.

3.2.2. *Single-element types*.—The single-element variable inductance pick-up is one in which the movement to be measured varies the inductance of one coil only, by either the variable air gap or core method. Figs. 10a and 10b show in diagrammatic form the two arrangements of this type. That of Fig. 10a has a variable air gap and consists simply of a small iron cored coil with an air gap in its magnetic circuit. The moveable armature is kept in position by flexible metal strips of the required physical characteristics so that the movement of the armature is proportional to the magnitude of the physical phenomenon under measurement. Most of the reluctance of the magnetic circuit appears in the air gap. Movement of the armature towards or away from the alternating current energised iron cored coil decreases or increases, respectively, the reluctance of the magnetic circuit and thus changes the inductance of the coil provided the exciting voltage is not sufficient to saturate the core. Fig. 10b illustrates the variable core type and consists of a coil of many turns of wire wound on a tube of insulating material with a movable core of magnetic material. As the magnetic core enters into the solenoid, the inductance of the coil increases in a manner approximately proportional to the amount of metal in the coil.

The above principles have been used as the basis of design of pick-ups for many measurements. For example, a strain unit on the variable core principle has been designed and used successfully by Messrs Rotols. A strain unit of the same type has been used very widely in Germany, particularly at the Luftfahrtforschungsanstalt, Brunswick, and the Aerodynamische Versuchsanstalt, Göttingen, where it is claimed that its stability, freedom from temperature sensitivity and degree of accuracy are vastly superior to the wire resistance strain unit. It was developed originally by Ratzke[8] and marketed by Siemens and further developed by Hinz and Kummerer[9], and a typical application is its use in wind-tunnel measurements by Kerris at the Luftfahrtforschungsanstalt[10].

A variable inductance seismic pick-up for the measurement of linear vibrations using the variable core principle has been designed at Royal Aircraft Establishment[11]. In this pick-up, relative motion between the elastically suspended core and the coil changes the volume of the former in the latter and consequently the inductance of the coil. The construction of this pick-up is shown in Fig. 11, which is self explanatory. This pick-up when used seisimically has a sensitivity factor of 0·077 microhenries per 0·001 inch displacement. Its measurement range is $\pm 0{\cdot}050$ inch and its response is faithful above 33 c.p.s. Its dimensions are $2 \times \frac{3}{4} \times \frac{3}{4}$ in. and weight approximately one ounce. It is designed for use with a carrier signal of a frequency of 1×10^6 c.p.s. in a tuned circuit type of precircuit to be described later.

For the measurement of fluid pressure the variable air gap type of inductance pick-up is the more appropriate[12]. Thus, in a pressure pick-up the armature takes the form of a thin diaphragm which is subjected to the pressure and whose resulting deflection varies the reluctance of the magnetic circuit and thus the inductance of the associated coil.

3.2.3. *Inductance ratio or 'push-pull' pick-up.*—The single element pick-up, while possessing the advantages of the variable inductance type in general, has several disadvantages due to the fact that it is both mechanically and electrically unsymmetrical, forming one arm only of the associated bridge circuit. Most of these disadvantages are overcome by designing the pick-up to form two working arms of the bridge circuit. The inductance ratio type of pick-up is thus one in which the movement to be measured causes a simultaneous change in two identical coils, increasing the inductance of one and at the same time decreasing that of the other by an equal amount. Therefore, it is a push-pull device. These push-pull units are more difficult to construct but they have several advantages over the single-element unit. The sensitivity is doubled, linearity of response improved and compensation for change in temperature, change in lead resistance and self-capacity is made easier. Like the single-element type, the push-pull type can use either the variable air gap or variable core principle.

A typical unit of this type using a variable air gap is the acceleration pick-up shown in Fig. 12. There are three essential parts to the pick-up, two laminated cores carrying alternating current energised coils and an elastically suspended laminated armature of ferromagnetic material. The two coil assemblies are attached rigidly to a light metal base and the armature is held symmetrically between the pole-pieces by flexible metal strips of 0·002 in. thickness. These strips allow the armature to move towards or away from the coils but not transversely. The elastic suspension has a resonant frequency of approximately 180 c.p.s. and the system is oil damped, the cover and base forming an oil seal. The unit is used as an acceleration pick-up over the range $\pm$ 12g and has linear response (error less than $\pm$ 5 per cent) over the frequency range 0 to 100 c.p.s. By the use of a single or double integrating stage the pick-up can be made to measure velocity or amplitude of motion, respectively, over the frequency range 2 to 100 c.p.s. The dimensions of the pick-up are $1\frac{3}{8} \times 1\frac{7}{16} \times \frac{7}{8}$ in. and it weighs approximately $1\frac{1}{2}$ oz.

Another example is a pressure unit developed at the Royal Aircraft Establishment and shown in Fig. 13. The differential pressure to be measured deflects the pretensioned steel diaphragm which is clamped between two identical iron cored coils. Movement of the centre of the diaphragm produces a push-pull change in the two coils. A typical unit for a range of $\pm$ 10 lb/sq in. has an undamped natural frequency of about 3000 c.p.s. and may be used in the frequency range zero to about 600 c.p.s.

Inductance ratio type variable air gap pressure pick-ups have also been used widely in Germany. The construction of a typical unit, developed at the Luftfahrtforschungsanstalt, Brunswick, is shown in Fig. 14, which shows a shaded section of the unit. The diaphragm, made of phosphor-bronze, so as to have good elastic properties, is placed symmetrically between the two coils. It is loaded in the region surrounding its centre by two discs of ferromagnetic material. Pressures may be applied to both sides of the diaphragm so that the unit can be used differentially. An interesting point in the design is the way in which the diaphragm is machined from the solid so that it is integral with the thick-walled cylinder forming the body of the unit. This avoids the possibility of deforming the diaphragm while clamping it into the body of the unit. This pick-up is used with a bridge circuit energised by alternating current of 5000 c.p.s.

Typical German variable inductance strain units of the moving core, variable air-gap and eddy current types are shown in Figs. 15a, 15b and 15c.

3.2.4. *Mutual inductance pick-up.*—Instead of designing the pick-up to give a measurable change in self inductance, change in mutual inductance can be utilised, the effective impedance of a coil being altered by change in the mutual inductance between it and another circuit. The most effective method of doing this is by changing the length of air-gap of the common magnetic circuits. Several pick-ups have been designed on this principle such as the pressure unit for static and transient pressures described by Baxter[13].

Mutual inductance pick-ups providing an out-of-balance current directly proportional to the displacement of the moving armature have been designed. They possess no general advantages over the self-inductance types but their application is more suited to some particular problems, such as the measurement of torsional displacement of rotating shaft.

3.2.5. *Advantages and disadvantages of variable inductance pick-ups.*—The advantages and disadvantages of the variable inductance pick-up compared with the wire resistance and capacity types depend to a large extent on the particular application and for many of these there is little to choose between the different types of unit. There are, however, some general points worth noting. Variable inductance units are, in general, very stable and can be used conveniently in conjunction with alternating circuits. They are therefore well suited for the measurement of static and slowly varying effects and for calibration by static methods. Compensation for temperature and other random changes are easily carried out in the push-pull designs ; in fact temperature effects can be made small by suitable design and by making the ohmic impedance of the coils small compared with their inductive impedance. They can be fairly easily constructed so that mechanical hysteresis is negligible.

In the case of the single-element unit with large air gaps care has to be taken in the installation of the unit as the nearby presence of large masses of ferromagnetic material may alter the calibration. As in other types of pick-up, frictional damping is always present especially where a ferromagnetic core is constrained to move along the axis of a coil, *e.g.*, in the seismic inductance pick-up described above. If care is not taken in the design and maintenance of the unit to reduce the frictional forces to negligible proportions, they can modify considerably the wave-form of the output. Suitable velocity damping can be introduced into the unit by one of the usual methods.

For the measurement of strain, variable inductance pick-ups have the advantage that the force they exert on the specimen does not alter appreciably with deformation of the specimen. This makes the unit suitable for long term application such as the measurement of static strain. On the other hand the size, weight and especially the increased distance of the working axis of the unit from the neutral axis of the specimen under test, as compared with that of the wire-resistance strain unit, is a distinct disadvantage.

Inductance pick-ups of low natural frequency are, in general, simpler to construct than the equivalent capacity units. Where high frequency response is required there is little to choose between the two types of pressure unit ; neither having a natural frequency as high as a piezo-electric type of the same overall sensitivity.

3.3. *Associated Circuits for Variable Inductance Pick-ups.*—The inductance pick-up is almost invariably energised by alternating current although direct current polarisation, described in Section 4, may be used. The frequency of this exciting current is determined by the frequencies under measurement, the latter modulating the former to a depth proportional to the change in inductance in the pick-up. The complete associated circuit must be capable of providing the energising current and amplifying and recording the resulting modulated alternating current. In this chapter will be described only that portion of the associated circuit which is concerned with the conversion of the inductance change into a proportional voltage variation. Such circuits can be divided into four main classes :—

(i) Series circuit.
(ii) Series—opposition circuit.
(iii) Bridge circuit.
(iv) Resonance circuit.

Although (i) and (ii) are used extensively for many measurements in industry they do not provide in general the sensitivity, stability and accuracy required in aeronautical engineering. For further information on the series and series-opposition circuits the reader, therefore, is referred to the literature[13].

3.3.1. *Bridge circuits.*—This is the most widely used circuit for use with variable inductance pick-ups. Assuming the unit itself, or the unit and its compensating inductance, form two adjacent arms of the bridge circuit, the remaining two arms have to be contained in the associated circuit. If the bridge is used with a current recording device of the desired frequency response, optimum conditions of sensitivity are obtained when the two fixed arms are also inductive. When the bridge is followed by an amplifier, its circuit can be simplified, the two fixed arms being made resistive[15,16]. This is convenient where multi-channel recording is used.

It is sometimes necessary to provide in-phase and quadrature balance in the alternating current bridge circuit, especially if a high-frequency carrier is used and the succeeding detector is not phase discriminating. Generally, however, at frequencies of carrier voltage used for the type of physical measurements discussed here, it is sufficient to provide resistance and inductance balancing only. The former is necessary because, near balance, the sensitivity of the bridge decreases rapidly with increase in resistance out-of-balance. Alternating current bridge circuits are discussed in more detail in Section 4 in connection with measurements of small changes in electrical capacity. The remarks made there apply equally well when the variable capacity unit is replaced by one utilising change in inductance.

The bridge circuit requires a constant voltage source of alternating current, the output voltage being independent, to a large extent, of the load impedance used, as any number of bridges may be fed from the common supply. Small variations in the supply frequency can generally be tolerated when a bridge circuit is used. For static or low frequency work up to 5 c.p.s. a stabilised 50 c.p.s. supply of low impedance is convenient, *e.g.*, the alternating current mains. Where a source of higher frequency is required a local oscillator of suitable design with a well-stabilised output is required. The bridge circuits are usually supplied from the energising source through a coupling transformer. Where more than one bridge is supplied from a common oscillator output transformer, care must be taken that there is no back-coupling.

Phase responsive self-balancing bridge circuits have been developed for the measurement of change in inductance and are in wide use. Their frequency response is very limited and for further information on these circuits the reader is referred to the literature [17,18].

3.3.2. *Resonance circuits.*—Another method of measuring small changes in inductance is by the use of a series or parallel inductance-capacity circuit. The inductance unit forms part of the inductance in the circuit which, if a null method is used, is usually tuned to resonance. If the null method is not used it is usual to partly tune the circuit and operate along the practically linear side of its resonance curve so that change in inductance of the unit gives a proportional change in the alternating voltage across the circuit. The circuit is equally well applied to the measurement of small capacity changes and it is described in more detail in Section 4.

As in the case of the bridge circuit, the accuracy of measurement with this type of circuit is limited by the constancy of the voltage of the alternating current carrier supplied to the circuit. The resonance circuit as compared with the bridge circuit suffers from the disadvantage that it does not permit of the use of push-pull units with the consequent loss of compensation for temperature and other changes. The tuned-circuit method, however, is capable of greater sensitivity than the bridge circuit, but, generally, the accuracy and stability that can be obtained from it are not so great.

Using inductance pick-ups and either of the two associated circuits described above, direct current response is obtained using alternating-current amplification only, detection, preferably of the phase discriminating type, following the necessary degree of amplification. Calibration of the unit and of the associated apparatus can also be carried out by static methods.

3.4. *Generator Pick-ups.*—3.4.1. *General.*—This class of electromagnetic pick-ups is termed generator type since most of such units generate a small e.m.f. proportional to the velocity of relative movement between a conductor and a permanent or electromagnet. It is best suited to the measurement of dynamic phenomena in which there is a considerable amount of power to actuate the unit. Mechanical energy must be introduced into the system by the structure under test and this is converted into electrical energy. This can be done in one of two ways :—

(i) By movement of a conductor through a steady magnetic field, *i.e.*, with the magnetic flux remaining constant.

(ii) By movement of part of a magnetic circuit so as to vary its reluctance and as a result to change the amount of flux through an associated search-coil, *i.e.*, with change of magnetic flux.

Many types of pick-ups have been designed on these principles. They have been used for the measurement of linear and torsional vibration, acceleration and fluid pressure. The pick-up is generally designed so that change in the physical phenomenon under investigation gives a proportional movement of its actuating part, this is turn generating an output voltage proportional to rate of change of movement. Thus, if the voltage output is to be proportional at any instant to the magnitude under measurement, integration must be used. The remainder of the associated apparatus is an amplifier of requisite gain and frequency response and a suitable recorder.

It must be borne in mind that this type of pick-up responds to rate of change only and so it cannot be calibrated or used statically. Dynamic methods of calibration such as those described in Section 6 have therefore to be used. On the basis of their mechanical characteristics, pick-ups of this type can be divided into two main groups—seismic and non-seismic. Typical examples of each type will be discussed.

3.4.2. *Seismic generator pick-up.*—This type belongs to class (i) above, the conductor and magnetic system being linked together by a weak spring so that above a certain frequency the relative movement between these two members can be considered equal to that of the structure to which the pick-up is attached. Either the conductor, usually in the form of a coil, or the magnetic system can be used as the seismic element. This pick-up is used widely for the measurement of linear or torsional vibration and a variety of different designs exist, some being available commercially.

Two seismic linear vibration pick-ups have been developed at the R.A.E. In both these units, the coil, wound on a copper former, forms the seismic part of the system. The magnet is fixed rigidly to the case. Copper is used as the material for the coil former so that its movement introduces eddy current damping, the amount of copper being adjusted to attain the desired damping factor of approximately 0·6. In one of these pick-ups the seismic element is supported by copper-beryllium diaphragms similar to those used in the Phillips vibration pick-up. A sectional drawing of this unit is shown in Fig. 16. The second pick-up has very weak helical springs supporting the seismic unit, the spindle of which moves axially in two ball-races, one at each end of the pick up, to minimise frictional damping. The output of each of these units is of the order of 0·5 volts r.m.s./in./sec and can be considered satisfactory above 30 c.p.s. The units are approximately 3 in. long, 2·0 in. in diameter and 18 oz in weight.

An associated development is that of a pick-up of the same principle designed for the measurement of torsional vibration up to a maximum amplitude of 3 deg. The supporting member of the unit, which is a coil, is secured to the shaft, and therefore, follows any irregularities in the shaft rotation, while a seismic element, comprising a magnet, is supported elastically. Due to its inertia this seismic element does not follow the irregularities but maintains an even rotation. Consequently, a voltage is generated which is proportional to the rate of change of relative motion of the parts. This voltage is led from the rotating shaft through resistance slip-rings. The voltage output of the pick-up for one degree amplitude at 20 c.p.s. is 150 mV.

3.4.3. *Non-seismic generator type pick-up.*—These pick-ups are operated below their natural frequency or have no elastic suspension. For instance, any of the above seismic units may be adapted to measure the movement of a structure relative to a fixed point, the seismic part of the unit being attached to the specimen under vibration while the remainder of the unit is attached rigidly to the fixed point. The elastic coupling between the two elements of the pick-up may be omitted. A pick-up of this type is used for ground resonance tests on aircraft and aircraft components by the method described in Section 11.

A typical example of a 'proximity' pick-up, depending for its action on the change of flux through a coil, is the Phillips Type GM5527. This consists of a bar shaped permanent magnet surrounded by a coil having a large number of turns and built into a case of ferromagnetic material. One pole of the magnet protrudes slightly from the end of the unit and is covered with a cap of non-magnetic material to serve as a mechanical enclosure and to complete the electrostatic screening. If a ferromagnetic object is brought near the 'open' magnetic pole the magnetic flux through the magnet, and thus through the coil, will change, and if the object is vibrating with respect to the pick-up, the changing flux will induce an alternating voltage in the coil proportional to the velocity of vibration. If the vibrating object is non-magnetic, a soft iron disc can be cemented to it. This pick-up cannot be considered a precision instrument as the sensitivity depends upon many factors such as the distance between the pick-up and vibrating object, the permeability, electrical conductivity and the dimensions of the vibrating object. It is, however, very useful as a measuring instrument where the vibrating object has so small a mass that the attachment of the pick-up would modify its characteristics, *e.g.*, in the case of thin membranes, strings, tuning forks, and rotating members. When used in conjunction with an integrating circuit (Type GM5522) amplifier and cathode-ray oscillograph (Type E.800) and if calibrated *in situ* this pick-up is capable of giving fairly accurate results. When 1 mm away from a soft iron surface its output is approximately 50 mV/in./sec. When used to measure amplitude of movement in conjunction with its associated circuits, its range is approximately 0·002 to 0·01 in. over the frequency range 1 to 1000 c.p.s. The relation between the sensitivity and the distance between the pick-up and moving object is not linear. To make the resultant distortion negligible it suffices to keep this distance at least ten times as great as the amplitude of the vibration. This pick-up weighs 1·5 oz, is 2·1 in. long and has a maximum diameter of 1 in.

Generator type pick-ups for the measurement of pressure variations are similar in principle to the vibration unit just described. Such a unit and its associated circuits have been developed by the Anglo-Iranian Oil Company[19]. The unit consists of a magnetic diaphragm moved by the pressure under measurement, and a magnet round the pole of which is wound a search coil. The unit has been designed to be very rigid so that the pole piece does not move appreciably with respect to the clamped edge of the diaphragm due to engine vibration. The unit has a small passage in front of the diaphragm in order, when measuring engine cylinder pressures, to cool the high-temperature gases before they reach the face of the diaphragm. The firm claim that this indicator passage is necessary whether the unit is water cooled or not in order to relieve temperature stresses set up in the diaphragm due to cyclic heating of the surface. Time delay and other effects occasioned by the presence of the orifice are claimed to be negligible. The maximum pressure range of the unit depends upon the thickness of the diaphragm. In the model for the measurement of aero-engine cylinder pressures the natural frequency of the diaphragm is of the order of 60,000 c.p.s. and linear response can be obtained up to at least 12,000 c.p.s. The overall calibration of the unit can be made linear to within $\pm$ 2 per cent of the maximum deflection. Magnetic hysteresis is negligible.

3.4.4. *Advantages and disadvantages of generator type pick-ups.*—As this type of unit responds only to rate-of-change of movement it is necessary to use an electrical integrating circuit when a measurement of amplitude is required. The integrating circuit attenuates the voltage signal from the pick-up and reduces the amount available for subsequent amplification. To counteract this, however, the initial generated signal may be made large by suitable choice of coil and magnet. Although a limit is placed on this by space and weight restrictions. Also, since the unit develops a voltage directly, the associated apparatus, including the integrating circuit, is simpler than that required by other types of pick-up. Besides the integrating circuit, an amplifier of suitable voltage or current gain and frequency response are required.

In virtue of its principle of operation the pick-up cannot be calibrated statically as in the case of capacity, inductance and resistance types. Units for the measurement of movement or rate of change of movement have to be calibrated on a dynamic calibrating table. Units, such as the one for the measurement of pressure variations, have to be calibrated against some other type of a measuring gauge such as a peak-reading gauge. The calibration of the unit is affected by the near presence of large masses of ferromagnetic materials. An advantage of the generator type pick-up is that as its impedance is, in general, low, long lengths of connecting cable can be used between the unit and the remainder of the apparatus without appreciable attenuation over the working frequency range.

3.5. *Associated Circuits for Generator Pick-ups.*—With the exception of the integrating circuits, the necessary associated equipment for use with generator type pick-up units will be described elsewhere. Briefly, the output from the pick-up and integrating circuit is of the order of a few millivolts and a voltage amplier with a gain of the order of 10,000 and with a suitable frequency response is required for the average application, if a cathode-ray oscillograph is used as a recorder. Integration and differentiation networks only will therefore be considered, the latter being included as they may be used in conjunction with a velocity responding pick-up when the required parameter is acceleration[20].

The theory of simple integrating circuits is considered only for sinusoidal input voltages as other wave-forms can, in practice, be resolved into a finite number of sinusoidal components covering a certain frequency range. If all frequencies in this range are faithfully integrated, so will be the non-sinusoidal wave-form. It is assumed, therefore, that the mechanical input to the generator type pick-up is sinusoidal, of pulsatance ω, and that the voltage output from the unit is a voltage of the same frequency proportional to the rate of change of the input, *i.e.*, proportional to the pulsatance ω for a fixed amplitude of vibration.

The simpler types of integrating circuits are shown in Fig. 17. The series resistance-capacity circuit is used extensively and the theory is briefly considered here. If a sinusoidal voltage $E = Ee^{i\omega t}$ is fed into the circuit at AB; E being the peak value of the voltage, e the exponential function, i the square-root of -1, it can be shown that the modulus $|V|$ of the voltage appearing across DE is given by

$$|V| = \frac{\omega \int E\,dt}{\sqrt{1 + \omega^2 C^2 R^2}} \qquad (1)$$

and the phase angle ψ between voltage input and output is given by

$$\tan \psi = -\omega C R \qquad (2)$$

If $\omega C R >> 1$, equation (1) can be rewritten

$$|V| = \frac{1}{CR} \int E\,dt \qquad (3)$$

and the phase angle approaches 90 deg lag ; *i.e.*, the output voltage is proportional to the integral of the input voltage when R is large in comparison with $1/\omega C$, *i.e.*, when the ohmic resistance of R is very large compared with the impedance of the condenser. Where a range of input frequencies is considered this condition has to hold at the lowest frequency it is required to integrate.

The smaller the impedance of the condenser compared with that of the resistance the more accurate the integration and the greater the attenuation of the circuit. This latter effect is undesirable as the input signal is, in general, already small. In practice a compromise between accurate integration over the whole of the frequency range and loss of signal amplitude is made. In general, if the impedance of R is ten times that of C at the lowest frequency, then sufficiently accurate integration is obtained, for then,

$$\omega CR = 10$$

and substituting in equation (1) gives

$$|V| = \frac{0{\cdot}995}{CR} \int E\,dt$$

while the phase angle ψ is 84·5 deg. The error involved in amplitude response is thus 0·5 per cent. Where lower accuracies of integration can be tolerated the value of CR can be correspondingly decreased in order to decrease attenuation. This of course is considerable in the above case, only one eleventh of the input voltage appearing across the condenser. This attenuation generally necessitates an extra stage in the amplifier of the associated apparatus when it is used in conjunction with a generator type pick-up and integrating circuit of the above type. In order not to distort the input signal the integrating circuit must present a relatively high input impedance.

Where successive integration is required, *e.g.*, to transform the signals from a pick-up responding to acceleration into amplitude of movement signals, two stages of the above circuit can be used, preferably separated by a high impedance such as a high-impedance amplifier stage.

Use of the circuit shown in Fig. 19b gives the same result although it is not used as extensively as that just described—possibly because it is generally easier to obtain a condenser of a particular value than it is an inductance.

The above circuits have the disadvantage that the output voltage can only be a small fraction of the input if true integration is required. An interesting development of the basic circuit described above has been described by Beale and Stansfield[19]. It allows of accurate integration when the relative impedances of R and C are lowered so as to allow 50 per cent or more of the input voltage to appear across the output. Its method of operation is, briefly, as follows. Referring to Fig. 19 and using the same nomenclature as above, equation (3) gives the condition for true integration as

$$|V| = \frac{1}{CR} \int E\,dt. \qquad (4)$$

If i is the instantaneous current flowing through C and hence through R then,

$$|V| = \frac{1}{C} \int i\,dt. \qquad (5)$$

From equations (4) and (5) it is seen that for true integration the relation $i = E/R$ has at all times to be satisfied. This is only so when the voltage across R is virtually equal to the input voltage E. If, however, the output voltage is amplified and a fraction of it equal to v is fed back, in phase, into the input of the integrating circuit so that a voltage $(E + v)$ is applied across the input terminals, then the voltage across R at any instant is equal to E exactly, irrespective of the value of V and the condition for true integration is satisfied.

A limit to the magnitude of the pick-up output voltage allowed to appear across C is set by the accuracy to which the feed-back voltage can be controlled. It is not practicable to make the voltage across C greater than the input voltage. This integrating circuit has been incorporated in the engine indicator amplifier made by the Anglo Iranian Oil Company.[19]

The basic differentiating circuits are similar to those of Fig. 17, except that in this case the output voltage is taken across R or L. If the circuit of Fig. 17a is used, then for accurate differentiation the impedance of R must be small compared with that of the condenser at the highest frequency to be differentiated. The phase of the output differentiated voltage leads the input voltage by 90 deg. Attenuation is introduced by the network and as in the case of the integrating circuit a compromise has to be made, generally between true differentiation and attenuation of the input signal. Where double differentiation is required this can be done by the use of two such circuits separated by a high impedance.

Integration over a limited range of frequencies can be obtained using the differentiating circuit of Fig. 17a in conjunction with an amplifier. To do this, part of the output of the amplifier is fed-back through the differentiating circuit and if the appropriate conditions are observed, the resultant output, over a limited frequency range, can be considered proportional to the integral of the input.

If ω_1 and ω_2 are the upper and lower limits of pulsatance over which integration is required, and A and A' the gain of the amplifier without and with feed-back, respectively, then it can be shown that

$$A' = \frac{1}{\omega CR} \times \text{Input} \qquad \text{(6)}$$

over the range ω_1 to ω_2 with errors of -2 per cent and $+2$ per cent of the correct value at the lower and upper frequency limits, respectively, if

$$\omega_2 CR \leqslant 0{\cdot}2 \qquad \text{(7)}$$

$$\omega_1 CRA \geqslant 5\,. \qquad \text{(8)}$$

Expression (6) shows that the amplitude of the output is proportional to the integral of the input amplitude. Conditions (7) and (8) refer to a sinusoidal waveform only, but similar conditions can be worked out for periodic waveform of other shapes, *e.g.*, square and triangular signals.

Taking as an example the frequency range 2 to 40 c.p.s., the limiting conditions in expressions (7) and (8) reduce to

$$CR = 0{\cdot}0008$$

$$A = 500.$$

The resultant voltage gain of the amplifier at the lower frequency limit will be approximately 100.

This method of integration has the advantage of producing a very stable amplifier, the feed-back being enough to make the output substantially independent of valve characteristics etc. It is widely used where an output proportional to the integral of the input is required over a limited frequency range.

4. *Variable Capacitance Pick-ups and Associated Circuits.*—4.1. *Principle.*—The electrical capacity of a condenser is a function of the overlapping area of its plates, of the separation between them and of the mean dielectric constant of the material between the plates. Thus, the variable capacitance method may be used to measure any mechanical effect which can be made to produce a proportionate and measurable change of capacity by means of a change in one or more of these three parameters. The change of area of overlap and of separation are most widely used, the change in mean dielectric constant being of more limited application, although it has been employed for the measurement of fuel content in aircraft tanks[21], and of the degree of aeration of oils.

The change of area of overlap system is useful for measuring angular and fairly large linear movements, and has the advantage that the capacity change, ignoring edge effects, is linear with movement.

For the measurement of small movements, or of quantities which can be measured by producing them, the variable plate separation method is preferable. The capacity C between two plates of overlapping area A, separated by a thickness d of material of mean dielectric constant

K is given by $C = KA/4\pi d$. This shows that the variation of C with d is hyperbolic, and not linear. This disadvantage may be overcome in practice by one or two methods :—

(i) By arranging that the capacity change is small compared with the initial capacity.

(ii) By making the dielectric partly air and partly a material of high dielectric constant, usually mica, and arranging that the moving plate is supported or clamped around its edges. The centre of this plate experiences the maximum deflection until it makes contact with the mica, and after this the mica reduces the effective movement of the plate. The extent of this reduction can be made to overcome the excessive rate of change of capacity as the plate separation decreases.

Even if mica, or other solid dielectric, is not employed the clamp plate method tends to improve linearity, at the expense of halved sensitivity, but the range of movement is limited by the plates coming into electrical contact.

If the two plates are parallel under all conditions it can be shown that, for a constant plate area and equal sensitivities in terms of capacity change against plate separation, the degree of linearity is the same whether mica is employed or not. The distance between the two plates is greater, however, when mica is employed and as this distance is very small, construction is made easier. If the comparison is made on the basis of equal electrode separations the use of mica increases the sensitivity and decreases the degree of linearity, its effect being the same as a decrease in plate separation if the dielectric were air only.

Further advantages of the use of mica are that the unit is more robust electrically, as there is less risk of accidental short circuits between the plates and higher potentials may be applied between the plates without flashover ; there is also an increased inherent mechanical damping in the system in some cases. Roess states[22] that the calibration is maintained over longer periods if air only is employed, but many pick-ups have been constructed employing mica in which no long-term instability was encountered.

Symmetric or push-pull type variable capacitance pick-ups have not been developed to the same extent as their counterpart in the electromagnetic type. They, however, possess the same advantages when used in conjunction with bridge circuits.

Variable capacity pick-ups are suitable for the measurement of movements, vibration, accelerations and static or dynamic strains and pressures. Typical examples of each will be discussed.

4.2. *Typical Pick-ups.*—4.2.1. *Vibration pick-up.*—The variable capacitance method has been used for the measurement of both linear and torsional vibration, although for linear vibration the generator type pick-up discussed in Section 3 is now more widely used. The advantages of the capacity method are its robustness and its amplitude response (the generator type responds proportionally to velocity and requires the use of an integrating circuit if the amplitude or vibration is required). Its disadvantages are the need for a comparatively complex precircuit and the limited cable lengths with which it can be used, even when the cable is the bulky low-capacity type. Further, vibration of the cable can produce signals indistinguishable from those of the pick-up, due to changes in cable capacity.

For both linear and torsional vibrations, the variable area method is more widely used than the variable plate separation method, as the amplitudes are usually too large for linear operation of the latter. In the case of linear vibration a cylindrical condenser is used, one plate being fixed rigidly to the case of the pick-up, the other being attached to a fixed point external to the vibrating member if such a point is available or, if not, is made part of a seismic system by coupling to the case through a weak spring. If extra mass is required to attain a low natural frequency the latter plate may be loaded. Damping is either fluid or eddy-current, but the need to introduce a magnet system purely for eddy-current damping is inconvenient.

A serrated condenser pick-up for measuring torsional vibration[23] is shown in Figs. 18a, b and c. It is arranged to fit into the pinion driving shaft of an aircraft engine, and measures the angular twist in a definite length of this shaft. To one end of this length of shaft a hollow cylindrical plate with internal longitudinal serrations is rigidly attached, and to the other end a second cylindrical plate with corresponding external serrations is similarly attached. The second cylinder is coaxial with the first, and of smaller diameter, so that its serrations form small condenser elements in conjunction with those of the other plate, the total capacity varying with the area of overlap, and hence with the twist. The gap between the elements is maintained by pre-loaded ball bearings. The pick-up is normally fitted so that inner and outer serrations half overlap when the shaft is transmitting approximately full mean torque and this gives the fullest range of linearity on either side of this torque. Sealing rings are used to keep oil out of the pick-up. The capacity change is linear with twist, and the unit is only slightly temperature sensitive.

A problem peculiar to pick-up units which are rotating in operation is the method of conducting the signal from the pick-up to the amplifying and recording equipment. This constitutes a major problem, as spurious signals can be introduced by the rubbing contacts which are usually necessary. If slip-rings with metal brushes are used they must be such that the capacity introduced by the rings is constant. Constancy of resistance is not so important, within limits. The slip-rings can be mounted on discs of insulating material which rotate with the shaft, rings on the periphery or face of a disc being equally satisfactory. Suitable ring materials are silver or stainless steel, the brushes being silver carbon. In general, it is preferable to use rings for bringing away both ' live ' and ' earth ' leads, as reliance cannot be put on an earth connection to the rotating shaft. Other methods that have been used with success comprise capacity between the rotating member and a stationary condenser plate, and a pin projecting from the axis of rotation of the rotating member, piercing a wash-leather diaphragm in a mercury container, the fixed lead to the equipment being taken from the mercury.

4.2.2. *Force pick-up.*—The variable capacitance technique provides a convenient method of measuring the total force in a member. The pick-up may be attached to the member under test or, in cases where a suitable attachment does not exist, as in the measurement of the tension in a cable, a special member or link may be introduced on which the pick-up is mounted. Fig. 19 shows a parallel plate condenser pick-up which was attached to the struts connecting an airborne lifeboat to a Lancaster aircraft in order to determine the aerodynamic forces exerted on the lifeboat in flight to assess their effect on the aircraft. These forces produced a strain in the strut which was measured with the variable capacity unit. This was attached to the strained member, made of Duralumin, so as to span a 5 in. length and give an initial plate separation of about 0·01 in. The dielectric was air only, and the gap between the plates was made large compared with their relative movement to attain linearity. It was arranged that the estimated maximum force produced approximately 20 micro-microfarads change of capacity.

A pick-up, incorporating a cylindrical condenser, has been designed for the measurement of force in a wire glider tow-rope. Owing to the lateral flexibility of the tow-rope the above pick-up unit is unsuitable and therefore, a calibrated spring is introduced into the rope, The condenser being used to measure its deflection. Referring to Fig. 20, it consists of two concentric brass cylinders, attached to opposite ends of the spring, the inner moving in guides with respect to the outer. The capacity change is thus directly proportional to the extension of the spring, and therefore, to the force in the tow-rope. The gap between the effective areas of the cylinders is approximately 0·015 in., and full extension of the spring produces a change of capacity of approximately 20 micro-microfarads. Edge effects in the condenser, which are discussed more fully in Section 4.2.6, are made negligible by arranging that the inner cylindrical plate is always well within the outer cylinder.

The methods discussed in this section are suitable for the measurement of total force. It is obvious that similar methods can be used for the measurement of strain, although the movements are usually so small that the variable separation, and not the variable area, method must be used.

4.2.3. *Strain pick-up.*—For strain measurement a compact capacity pick-up unit has been developed by Shannon[23]. This is shown in Fig. 21. It consists of two pressure plates, A, and a flexible adjusting ring B, which carries a ' sandwich ' capacity element C, consisting of two pairs of flat springs D and E, made encastré at their ends in the slots of the ring B by means of a metal wedge W. The outer springs D and E, are insulated all over by means of a thin layer of mica. The two pairs of springs are separated by a piece of strip rubber or polystyrene R to ensure equal pressures on them. The curved faces of the pressure plates A transmit the movement, due to the strain in the member to which the gauges are attached, to the condenser elements formed by the earthed springs D and the insulated springs E. The number of pairs of springs can be altered to produce any required capacity change. The diameter of the unit is $\frac{7}{8}$ in.

The employment of capacity strain gauges has decreased markedly since the development of reliable wire resistance types. Compared with these the capacity gauge has the following disadvantages :—

(i) The comparatively complicated construction, combined with the narrow limits of accuracy necessary in its manufacture. This also makes it difficult to construct a batch of gauges with similar characteristics of sensitivity and linearity.

(ii) The thickness and height above the surface to which it is attached. If this surface bends the gauge suffers a greater movement than the strain in the surface. Also, if the surface is external on an aircraft or propeller, the gauge disturbs the airflow and may result in turbulent conditions that would not exist in the absence of the gauge.

(iii) The weights, which result in excessive forces in the cement by which it is attached to the structure if there is a high acceleration at the point of attachment. This is particularly troublesome when the gauge is used on rotating propellers. The gauge is, in any case, difficult to attach to curved stressed-skin structures. Despite these disadvantages the capacity strain gauge is by no means obsolete, and is still used on surfaces at temperatures at which the wire resistance gauge would be damaged.

4.2.4. *Pressure pick-up*.—The capacity type pick-up has been applied extensively to the measurement of steady and fluctuating pressures, especially in the cylinders of reciprocating engines. The basic form of this type of pick-up is represented by Fig. 22. The condenser is made up of a metal plate rigidly fixed to the body of the unit, and insulated electrically, while the other plate, to whose outer surface the pressure is applied, is a metal diaphragm whose periphery is also rigidly fixed to the body. The gap between the two plates may be air only, or partly filled with mica, as discussed in Section 1. Pressure on the outside of the pick-up causes the diaphragm to deflect and produces a capacity change. The sensitivity of the unit is controlled by the thickness of the diaphragm, being approximately inversely proportional to the cube of this thickness, while the natural frequency is approximately proportional to the thickness. This type of pick-up has been developed by Southern Instruments Ltd.[24]. Other capacity pick-ups for this work have been developed by Dodds[25], who used a gap partly filled with mica, and Roess[22]. The latter employs an air dielectric only, for the reasons given in Section 1, in conjunction with a bridged-T balancing circuit, which is built into the pick-up head to reduce capacity changes due to lead wire vibration. This makes the overall dimensions of the pick-up large, a serious disadvantage for the measurement of aero-engine pressures. The bridged-T balancing circuit is discussed more fully in Section 4.4.5. Roess's pick-up incorporates the diaphragm integral with the outer case, and linearity is obtained by ensuring that the movement of the diaphragm is small compared with the electrode spacing. In all cases the pick-up is arranged either to screw direct into the cylinder head of the engine, or into an adaptor which is screwed into the cylinder head.

The types of pick-up described in the previous section are satisfactory for work at normal room temperature, and, if calibrated under the same temperature conditions as those under which they are used, for work at high or low constant temperatures. If the temperature is either varying during the period of measurement, or such that a severe thermal gradient exists along the pick-up, as when it is used for measuring the pressures in the cylinders of reciprocating engines, a water-cooled unit is used. A type developed at the R.A.E. is shown in Fig. 23. All the pick-ups described in this section respond directly to pressure, and if a record of rate of change of pressure on a time scale is required, differentiation may be effected electrically in the amplifier.

4.2.5. *Acceleration pick-up.*—The pressure sensitive unit previously described and shown in Fig. 22 may be used in a pick-up responding to acceleration, the force on a known constant mass being applied to its centre through a rigid transmission. The diaphragm of the pressure pick-up, which forms the spring of the accelerometer, then deflects an amount proportional to the force on the mass. No damping other than that inherent in the materials is incorporated, and accelerations at frequencies up to about 0·2 of the natural frequency (decided by the stiffness of the diaphragm and the mass) may be recorded with no appreciable errors of amplitude or phase. Any unwanted shock excitation of the natural and higher frequencies can be filtered out electrically in the amplifier. Two typical examples of capacity acceleration pick-ups are shown in Figs. 24 and 25. The former is suitable for comparatively small accelerations, and by suitable choice of the diaphragm thickness may be made to cover any range from 0 to 1g to 0 to 100g. The ' top-hat,' A, forms the mass together with the force transmitting rod, B, which terminates in the hemisphere, C, which is in contact with the diaphragm D, of the condenser unit. By screwing down B, so that C is forced against D by tension in the diaphragms E, the zero of the pick-up may be set anywhere in the working range, *i.e.*, an accelerometer recording 0 to 10g when it is not pretensioned in this manner, may be made to record $\pm 5g$ with pretensioning, without the hemisphere C moving away from D at $-1g$ as would otherwise occur.

The second type (Fig. 25) is suitable for measuring accelerations between 100g and 1,000g. The mass in this case is a steel ball resting on the diaphragm of the condenser unit. The principles of operation are the same as in the previous type and a similar method of zero displacement is used.

It can be shown that the natural frequency, f_n, of an acceleration pick-up is related to the maximum acceleration, $g_{\max}$, which it will record with a spring extension $\delta_{\max}$ by the expression :—

$$f_n = \frac{1}{2\pi}\sqrt{\frac{g_{\max}}{\delta_{\max}}}.$$

This shows that if the maximum acceleration, expressed in terms of the acceleration due to gravity, is fixed, the natural frequency, which should be as high as possible to enable the maximum range of frequencies to be recorded, is dependent only on the smallest measurable movement that can be made to correspond with the maximum g. If this movement is fixed, the relation can be rewritten $f_n = k\sqrt{(g_{\max})}$ and the practical value of k for a capacity accelerometer has been found to be approximately 160. The capacity acceleration pick-up suffers from the same disadvantages as the pressure unit, obtaining the desired sensitivity and linearity being tedious, and it is considerably larger than the variable inductance and resistance types. It has the advantages of good stability over long periods, and is not easily damaged by overloading.

4.3. *Edge Effects in Variable Capacitance Pick-ups.*—The factors affecting linearity of capacity change with change of magnitude of the applied mechanical effect that have been so far considered have not included the distortion of the electrostatic field of a condenser at the edges of its plates. If this effect is not allowed for, the measured capacity of a parallel-plate condenser is larger than the calculated value. As the requirement in a pick-up is that the change of capacity is linear with movement, this effect would be of no consequence if it remained constant for all working positions of the plates. In theory, this is not the case, the edge effect varying with the plate separation and relative displacement of the plates in their own plane. In practice, the variation of capacity due to edge effects is small and can usually be made negligible.

Kirchoff has deduced an expression for the capacity, C, of a condenser with circular parallel plates[26]

$$C = \frac{R^2}{4D} + \frac{R}{4\pi D}\left[D\left\{\log_e \frac{16\pi R(D+t)}{D^2} - 1\right\} + t\log_e\left(1 + \frac{D}{t}\right)\right]$$

where R is the radius and t the thickness of each plate, and D the separation between them. Calculations based on this expression show that in the case of variable separation pick-ups with plate separations of a few thousandths of an inch, and plate areas of about 10 sq in. the change in edge effect is only of the order 0·05 per cent of the change of capacity due to change of plate separation.

In the pressure pick-ups discussed the effect is even smaller as the plates are of different diameters, and the minimum movement occurs at the edges. In variable area pick-ups of both the cylindrical and serrated types the effect is minimised by limiting the movement so that the edges of the two plates overlap by a distance always more than twice the air gap.

4.4. *Conversion Circuits for Capacity Pick-ups.*—The changes of capacity produced in the pick-up by the mechanical effect under measurement have to be converted into corresponding voltage variations by means of a suitable 'pre-circuit.' These precircuits may be classified into the following groups :—

(i) Direct current polarisation circuit.

(ii) Alternating current bridge circuit.

(iii) Tuned circuit with amplitude modulation.

(iv) Frequency modulation method.

(v) Bridged-T balancing circuit.

(vi) Beat note method.

Each of these types, with typical examples where necessary, will be discussed.

4.4.1. *Direct current polarisation circuit.*—The simplest method is to connect a resistance, R, in series with the capacity pick-up and a battery. If the capacity change is of very short duration compared with the time taken for the condenser to discharge through the resistance, the charge, Q, on the condenser is almost constant, and the increase, δC, in the initial capacity C, results in a change δV in the voltage V across the condenser in accordance with the relationship :—

$$\delta V = -\frac{V\delta C}{C} \text{ (neglecting the term } \delta C\,\delta V).$$

Thus, for a fixed value of C and V, δV is proportional to δC. Despite the attraction of the simplicity of this circuit it suffers from grave disadvantages in practice, particularly in the measurement of low frequency phenomena. In order that Q may be assumed constant the time constant, $C \times R$, of the circuit has to be long compared with the duration of the signal. If C is made large to effect this the sensitivity $\delta V/\delta C$ is reduced. On the other hand, if R is increased, instability in the amplifier and other effects accompanying the use of a high resistance become serious. A further disadvantage is that the measurement of a sustained effect or the static calibration of the pick-up is impossible.

This type of circuit is used in the Cossor-Dodds electronic pressure indicating equipment in conjunction with the Dodds pick-up mentioned in Section 4.2.4. Provision is made for selecting battery voltages in five steps from 12 to 120 volts, and the frequency range is claimed to be from 2 to 50,000 c.p.s.

4.4.2. *Alternating current bridge circuit.*—The disadvantages of the direct current polarisation circuit are overcome by connecting the pick-up as one arm of an impedance bridge energised from an alternating current source. A suitable circuit is shown in Fig. 26. The bridle-energising alternating current is applied through the transformer T_1, whose ratio is selected to match the impedance of the alternating current source to that of the bridge, while the output transformer T_2 matches the output impedance of the bridge to the input impedance of the amplifier. R_1 and R_2 are the fixed arms, whilst C is the pick-up. The bridge may be balanced by adjusting the capacity of the condenser C_1 across the pick-up. Even when $C_2 = C_1 + C$ the bridge is in general not in perfect balance owing to the out-of-phase component produced by the difference in power factor between C_2 and $C + C_1$. To balance out this component, R_3, which is in either the arm containing C_2 or C_1, is adjusted. Changes in the pick-up capacity then produce corresponding changes in the amplitude of the out-of-balance A.C. voltage. The amplitude modulated carrier may be amplified and applied to an oscillograph as discussed in Section 7 or may be demodulated by a sense-discriminating detector and amplified for application to a cathode-ray tube. The choice of the frequency of the energising source is governed by the maximum frequency to be recorded and by the effect of leakage resistances of the condensers. This frequency must be at least five times that of the highest frequency to be recorded. Even if this condition is satisfied the frequency must be sufficiently high to make the reactances of the arms C_2 and $C + C_1$ not more than about 100,000 ohms for work under flight or field conditions so that the effects of dampness and leakage are minimised. On the other hand, an unnecessarily high frequency carrier may lead to difficulties with stray capacities and inductances.

4.4.3. *Tuned circuit method with amplitude modulation.*—In this method a high-frequency carrier signal is amplitude modulated as the result of the capacity change in the pick-up. It was first applied to the measurement of pressure by the Southern Instrument Co[24]. The method employs the change of amplitude of the voltage across a tuned inductance-capacity circuit with the degree of mistuning of the circuit. A resonance curve may be plotted relating this amplitude with capacity for a fixed value of the inductance. Although there is no part of this curve over which the voltage is exactly proportional to the capacity change, there is a small range on each side of resonance over which the relationship is sufficiently linear for practical purposes. Thus, if the capacitance pick-up is made part of the capacity in the tuned circuit, variations in its capacity can be made to produce proportional changes in amplitude of the voltage across the tuned circuit. It is ensured that the total capacity in the tuned circuit and the capacity variations are always such that the conditions are represented by points on the linear portion of the resonance curve. This necessitates the adjustment of the total capacity in the tuned circuit so that, when the pick-up is under its initial conditions, the working point is at the appropriate end of the linear portion if a unidirectional effect is under investigation, or at the centre for a bidirectional effect. The carrier frequency is then amplitude modulated by the variations in pick-up capacity. The modulated signal is rectified, after amplification if necessary, and the carrier frequency filtered out, leaving the modulating voltage which varies proportionally to the pick-up capacity. After further amplification the signal is applied to a cathode-ray tube or vibration galvanometer.

The basic elements of the precircuit are a high-frequency oscillator, the tuned circuit and the detector. This simple arrangement is not entirely satisfactory, as the varying impedance of the tuned circuit produces changes in the frequency and output voltage of the oscillator, and similar changes are also produced by changes in the operating voltages of the oscillator valve. To overcome these disadvantages a 'separator' or 'buffer' valve is interposed between the oscillator and the tuned circuit. It is arranged that this valve is operated over the whole of its (anode current-grid volts) characteristic, and the carrier voltage is sufficient to drive the valve beyond both saturation and cut-off. The carrier is distorted at the anode of this valve, but the tuned circuit does not respond to the harmonics thus produced.

The choice of the frequency of the carrier is influenced by the following considerations :—

(i) The initial capacity of the pick-up with connecting cable and the capacity change produced.

(ii) The damping of the response curve introduced by the cable between pick-up and precircuit.

(iii) The desirability of a fairly sharp response curve for the inductance-capacity circuit, to obtain sufficient sensitivity.

(iv) The need for linearity over the operating range.

(i) and (ii) set the upper frequency limit, (iii) and (iv) the lower. In practice, it has been found that a frequency of about 1×10^6 c.p.s. is a good compromise. This, when an inductance of 25 microhenries is used requires a total capacity of about 1,000 micro-microfarads. The pick-up capacity is usually 100 to 200 micro-microfarads and these values permit up to about 50 ft of low-capacity (15 micro-microfarads per foot) cable to be used.

4.4.4. *Frequency modulation method.*—A precircuit has been developed by Messrs. Southern Instruments making use of frequency modulation. The pick-up forms part of the frequency controlling circuit of a 2×10^6 c.p.s. oscillator, to which it is connected by a lead of about 6 ft. The output voltage of the oscillator is fed to the remainder of the precircuit by twin cable which may be several hundred yards long. It is then amplified and applied to a frequency discriminating circuit, having equal inductances and slightly different capacties, resulting in slightly different resonant frequencies. The circuits may be tuned by ganged variable condensers, in such a way that there is always the same excess capacity, approximately 30 micro-microfarads, in one of them. The high-frequency voltages across the two circuits are rectified by the two sections of a double-diode, whose load resistances are so connected that a direct current voltage proportional to the difference between the two high-frequency voltages is developed across them. The curve connecting direct current output voltage with frequency of the applied high-frequency voltage (which is proportional to the capacity) is N-shaped. By correctly adjusting the relative resonant frequencies of the two tuned circuits the central limb of the diagram can be made linear where it crosses the zero voltage line, and this point is the working-point of the discriminator. The range of capacity change that can be handled is approximately 0 to 20 micro-microfarads.

The advantage of frequency modulation over the tuned circuit method is that from the point at which the capacity variation is converted to a change of frequency up to the discriminator, attenuation distortion introduced by the electronic circuit and connecting cable is of no importance. This means that the oscillator must be located close to the pick-up but a long cable can be used to connect it to the remainder of the circuit and recording equipment, which can be beyond the zone in which microphony produced by the phenomenon under investigation is troublesome. On the other hand, the oscillator has to be very free from microphony, owing to its proximity to the pick-up.

4.4.5. *Bridged-T balancing method.*—As stated in Section 4.2.4, the capacity pressure pick-up used for engine indicating by Roess was made linear over the full pressure range by making the movement of the diaphragm very small compared with the air gap. The percentage modulation that could be obtained by any direct application of the carrier to the pick-up through another condenser or resistance would be only about 0·1 per cent, and this would place severe requirements on the level of stray modulation. It was decided that a balancing circuit of bridge type would prevent this, and a capacity bridge of the type discussed in Section 4.4.2 was tried, using a double bridge in an attempt to balance out the capacity changes due to vibration of the wires connecting the pick-up unit to the precircuit. This was not successful and the bridged-T circuit shown in Fig. 27 was finally used. This gave high percentage modulation, and when the inductances L_1 and L_2 were built into the head of the pick-up, minimised the effects due to vibration of the lead wires. The remainder of the balancing circuit was housed in the radio-frequency amplifier which followed it. The balancing circuit was energised by means of an oscillator of frequency 4 megacycles per second. The modulated carrier from the circuit was then amplified, rectified, and the modulating component corresponding to variations in pick-up capacity applied after further amplification to a cathode-ray tube. A flat response up to 100,000 c.p.s. is claimed.

4.4.6. *Beat note methods.*—Ultra-sensitive methods of detecting a capacity change have been developed from the original scheme used by Whiddington[27]. A beat note is produced between the output voltage of a high-frequency oscillator, in which the pick-up capacity forms part of the frequency-controlling inductance-capacity circuit, and that of another oscillator of constant frequency equal to that of the first when the pick-up is in its initial condition. This results in a low-frequency beat note, the frequency of which is dependent on the change of capacity.

Although under laboratory conditions movements as small as 10^{-6} in. can be easily measured the low-frequency variation in the output is not convenient for recording purposes, as arduous computation would be necessary to deduce the final result. This disadvantage has been overcome by using a galvanometer to determine the change of current in the oscillating valve when the ratio of the capacity to the inductance is changed. The circuit then becomes less sensitive, and is not as satisfactory as the other methods described above, as very high-frequency stability is required in both the oscillators.

Other circuits have also been developed[28] using the same principle, but all suffer from stability difficulties, and from ' pulling-in,' *i.e.*, one oscillator tends to affect the frequency of the other, this effect being more marked when the two frequencies are close together, which occurs at the position of maximum sensitivity, where it is least tolerable.

4.5. *Optimum Capacity Variation in Capacity Type Pick-up Unit.*—In designing a capacity type pick-up it is necessary to decide a figure for the capacity variation that shall be produced by the full range of the mechanical phenomenon under investigation. The maximum is decided by the requirement for linearity of voltage output from the precircuit with capacity change. It is not usually practicable to compensate non-linearity of the pick-up with non-linearity of the precircuit, so that, in practice both the pick-up and the precircuit must be linear.

The maximum permissible capacity change in the pick-up is determined by the type of precircuit with which it is to be used. In the case of the direct current polarisation precircuit discussed in Section 4.4.1 the capacity change should be as large as possible consistent both with negligible change of time constant and with linearity in the pick-up. If a bridge circuit, discussed in Section 4.4.2, is used with a variable capacitance pick-up giving an unsymmetric capacity change with respect to earth, the bridge output is linear only over a limited range of capacity variation. This range is dependent on the initial impedances of the arms, but it is usually not difficult to obtain linearity within about $\pm$ 5 per cent over about 50 micro-microfarads. If a pick-up giving capacity changes symmetrical with respect to earth is used, the bridge sets no limit to the maximum range of capacity variation. It is possible by careful design to make the tuned circuits described in Section 4.3 and the frequency-modulated precircuit (Section 4.4) linear over a range of 30 to 40 micro-microfarads. To allow for possible movement of the operating point along the linear part of the response curve the pick-up is designed for a maximum capacity-change of 20 micro-microfarads.

The lower limit of measurable capacity variation is set by spurious effects such as capacity changes produced by vibration and temperature changes in the cables connecting the pick-up to the precircuit. To keep the total capacity of pick-up and cable low and to minimise damping of the tuned circuit where this is used, concentric low-capacity cable is employed in conjunction with suitable concentric low-capacity connectors. The lack of rigidity of the central conductor in this type of cable gives rise to small variations of capacity under vibration, which can be made negligible in practice if the capacity change corresponding to maximum variation of the mechanical effect is not less than approximately 5 micro-microfarads. To minimise the damping effect on the tuned circuit of the cables, or leads needing to be embedded in a dielectric for insulating purposes, distrene has been found to be a very suitable material. It absorbs water to a negligible extent, has very good insulating properties, low power factor and a comparatively low dielectric constant.

In the case of the engine indicator pick-ups of the Roess and Dodds (Section 4.2.4) types the capacity changes are only 1 or 2 micro-microfarads to ensure good linearity, but the bridged-T balancing circuit (Section 4.3.5) used by Roess neutralises capacity changes due to the cable. In practice it is necessary to compromise between the various factors discussed, and experience has shown that a maximum capacity variation of about 20 micro-microfarads, and certainly not less than 5 micro-microfarads, together with a tuned or frequency-modulated precircuit linear over 30 to 40 micro-microfarads represents the best combination.

4.6. *Advantages and Disadvantages of the Variable Capacitance Techniques.*—The choice of technique for a particular measurement demands consideration of the advantages and disadvantages of all possible techniques in relation to the conditions of measurement. The main advantages of capacity pick-up units are their robustness, constancy of characteristics over long periods, low temperature sensitivity if materials having suitable coefficients of expansion are employed, and ability to withstand high temperatures. The technique facilitates the measurement of very small movements, permitting high natural frequencies to be attained in accelerometers and pressure pick-ups. Disadvantages are the tedious and accurate work required in the construction of pick-ups, leading to difficulties in making units of predetermined characteristics, and the comparatively complex and bulky nature of the more satisfactory types of precircuit. The limited length of cable that can be employed between pick-up and recording equipment is a further disadvantage unless the frequency modulated precircuit is used.

The disadvantages outweigh the advantages for vibration measurements, for which the electromagnetic generator pick-up is more convenient, and for strain measurement at fairly constant temperatures up to approximately 80 deg C, for which wire resistance strain gauges may be used. The variable capacitance method, however, is very satisfactory for strain measurement at high temperatures, and for acceleration and fluid-pressure recording, in which it finds its widest application.

5. *Variable Resistance Pick-ups and Associated Circuits.*—5.1. *General.*—Electrical measuring instruments utilising change of electrical resistance are in wide use in mechanical and aeronautical engineering. In such instruments the physical phenomenon under measurement is converted in the pick-up into a corresponding change in electrical resistance. Variable resistance pick-ups may be classified into the following three main groups on the basis of the method used to bring about the resistance change :—

(i) Change of resistance by movement of a contact, thus changing the area or length of a resistance unit.

(ii) Change of resistance by change of temperature.

(iii) Change in resistance by change in dimensions.

5.2. *Moving Contact and Thermosensitive Units*[29,30,31].—Owing to the simplicity and adaptability of the moving contact principle, no standard form of this type of pick-up can be said to exist. Each application is, in general, considered independently and the most appropriate design to suit each particular case is adopted. An example of such a pick-up is that developed for the measurement of strut closure and tyre deflection during undercarriage drop-testing referred to in Section 11. A pick-up of this type has also been used extensively for the measurement of aircraft gun movements in their cradles during firing. These units are generally robust, simple in operation and frequently can be designed to give enough current or voltage output to operate recording instruments without added amplification. Their chief disadvantages are that they cannot be used to measure small movements of less than about 0·1 in. accurately, or operate at comparatively high frequencies such as are frequently encountered in the field of measurements dealt with in this report. Care has to be taken in their design to ensure a faithful reproduction by the moving contact of the movement being measured and to avoid chatter of the contact on the resistance, particularly in the presence of vibration or impulsive forces.

As the thermosensitive pick-up consists of a resistance element whose value varies with its temperature, when used to measure a physical magnitude other than temperature, that magnitude has to produce a temperature change in the unit. Generally, this change in temperature is the result of a change in the rate of heat transfer from the unit which is supplied heat at a constant rate. Thus the mechanical design must involve principles of heat transfer. This limits the scope of application of such pick-ups, their main application being to the instrumentation of gases for which they are unequalled. A well-known application of this nature is the measurement of turbulent flow in wind-tunnels which is referred to in Section 6. Like all thermal measuring instruments, their design demands careful consideration of their thermal properties and, in particular, their thermal inertia which sets a comparatively low limit to their frequency response.

5.3. *Strain and Pressure Sensitive Resistance Units.*—This type of unit has been used extensively, especially in the form of strip resistance strain units. Use is made of the fact that a change in dimensions of an electrical conductor causes a corresponding change in its resistance. In general, an additional resistance change takes place if the change in dimensions is accompanied by internal stress, a change in resistivity then taking place. Strain sensitivity in an element is usually accompanied by pressure sensitivity and it was this latter property that first drew attention to and initiated work on the subject. Application of this principle to the measurement of hydrostatic pressure is direct and, while the design of the pick-up is different from that for strain measurement the requirements for the associated apparatus are the same. No use has been made of this pressure sensitivity for measurements in the aeronautical field in recent years and the reader is therefore referred to the literature for further information[32,33].

Strain sensitive resistance units are generally constructed in strip form. They are simply strips of material comprising strain sensitive resistance material of known resistance and strain sensitivity. The strain sensitive material may be made of carbon composition, metallic film, or resistance wire.

The carbon composition strain unit[34,35,36] is the simplest type to manufacture and is the most sensitive. It has been used extensively for the measurement of strain, pressure, force and acceleration, although in recent years it has been largely superseded for quantitative work by the more stable wire resistance type. The carbon unit exists in many forms, the simplest being merely a strip of suitable dimensions of the material used in the production of radio composition resistors. This type has a number of undesirable features and many attempts, involving the material used and the physical design, have been made to improve it. A recent design, incorportating features which are claimed to remove many unwanted characteristics, consists of a multilayer strip of cloth reinforced plastic and carbon composition conducting material all moulded together to form a robust sealed unit which can be easily cemented to the test surface. This type of unit has been used widely in Germany although it is the strongly held opinion there that it is inferior in characteristics and performance to the inductance strain unit. It has been marketed commercially by A.E.G. Berlin, in the form of suspensions of carbon composition dust of various grades in a liquid which may be brushed on to a suitable base of paper or plastic material and thus formed into a strain-unit of the required resistance value and dimensions.

The carbon composition unit has the advantage that it is robust and many times more sensitive than a resistance wire unit of the same resistance. It, however, still suffers from a number of serious disadvantages such as instability, lack of reproducibility of calibration, hysteresis and sensitivity to vibration, change of temperature and humidity. The source of these errors appears to be inherent in the nature of the substance composing the unit. In addition, the range of strain over which it can be used is limited to about 0·2 per cent.

Resistance units of metallic film deposits on an insulated base have been investigated at R.A.E. One method involves a photographic process leaving a fine deposit of silver in the form of a grid on the celluloid base. Another method consists of sputtering the metallic film on to quartz fibres in order to form a strain sensitive conductor. In both these methods the conductor is in the granular form and the units consequently tend to suffer from the same disadvantages as the carbon unit regarding stability. For the above reasons, and also on the score of cost in the case of the photographic unit, this type of unit has not been used to any extent.

5.4. *Wire Resistance Strain Unit*[37,38,39,40].—5.4.1. *Principle.*—The resistance wire strain unit has been used extensively in recent years for both static and dynamic strain measurements. Its superiority over the carbon strip unit is well established in spite of its comparatively low strain sensitivity and, owing to the ease of construction of small thin units of this type, it is more applicable than the capacity and inductance types to measurement in aircraft structures. The latter, however, may be used with advantage where a unit of comparatively large dimensions may be employed.

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Briefly the unit consists of a grid of parallel fine resistance wires generally connected in series and moulded to a plastic base or cemented to a paper base. Its strain sensitivity is defined by the equation

$$s = \frac{\Delta R}{R} \Big/ e$$

in which ΔR is the change in its resistance R due to a strain e parallel to its axis : Theoretically

$$s = 1 + 2\sigma + \frac{\Delta \varrho}{\varrho} \Big/ e$$

where σ and ϱ are Poisson's ratio and the specific resistance respectively of the material of the wire. No reliable information exists on the variation of the specific resistance of fine wires with strain, but it has been found that there is a variation, which in some cases, *e.g.*, manganin, may be negative. This variation partly accounts for the wide range of values of s found experimentally for various materials. The fact that σ for fine wire may be different from its usual value for the same material, and may vary with the strain in the wire, is also a contributory factor. For the materials generally used in the manufacture of these strain units the strain sensitivity or gauge factor is about 2·1. Units having larger factors can be used but in general only at the expense of time and temperature stability, making high sensitivity strain units less suitable for static tests over long periods.

The temperature coefficient of resistivity of the wire and the differential coefficient of thermal expansion of the unit and the member to which it is cemented introduce another factor that affects the sensitivity of the unit. In dynamic measurements, however, the temperature sensitivity of the unit rarely proves troublesome as the temperature changes are usually sluggish and there is no necessity to provide temperature compensation as in the case of static measurements.

5.4.2. *Design and construction.*—To enable the unit to be used for the measurement of both tensile and compressive strains the strain sensitive wire is normally cemented or moulded to a suitable base. In use, this is in turn cemented to the test surface so as to form, to all intents and purposes, an integral part of that surface. In its simplest form it consists of a grid of parallel wires connected in series, the two ends of which are welded to two stouter connecting wires suitably anchored to the base. Wires of various materials and diameters are employed, the choice being determined by the strain sensitivity required with due regard to temperature sensitivity, resistance value and dimensions. A satisfactory material for general use is ' Brightray' wire (nominal composition 80 per cent nickel and 20 per cent chromium) of 0·0006-in. diameter. This wire is readily available, mechanically strong, has a high specific resistance of about 110 microhms/c.c. and a comparatively low temperature coefficient of resistivity of about 98×10^{-6}/deg C.

Strain units of various types have been available commercially in the U.S.A. for a number of years, the chief manufacturer being the Baldwin Southwark Co. They are now also manufactured in quantity by a number of firms in England such as Messrs. Tinsley, The British Thermostatic Co., Rolls Royce Ltd., Rotol Airscrews Ltd. and the de Havilland Aircraft Co.; various methods of manufacture are employed. A convenient method in wide use is to wind the wire on a flattened cylinder of impregnated paper, using a suitable coil-winding machine. Layers of impregnated paper are then placed over the wire and the whole unit bonded under pressure at a suitable temperature.

Although a very wide variety of strain units of different shapes, dimensions and gauge factors are now available, it is frequently found that certain applications require a special form of unit. It has therefore, been advisable to construct a simple jig for the construction of such units, on which the wire is wound under tension over a series of suitably placed pins which are removed after cementing the former to the paper base[41].

5.4.3. *Attachment of strain unit to test surface.*—For most applications in aeronautical engineering the strain unit is cemented to the test surface. Although the mass of the wire resistance strain unit is small it offers some restraint to the movement actuating it, since in order to strain the unit some force must be applied. Since this force must be transmitted through the adhesive with which the unit is attached to the test surface, the adhesive becomes part of the pick-up and its characteristics must be considered. The adhesive used must ensure that the strain experienced by the strain unit is to all intents and purposes, the same as that experienced by the specimen over the working range of the unit, and regardless of time and change in temperature. Owing to the small cross-sectional area of the wire resistance strain unit it has the important advantage over most other types that the force which has to be transmitted by the adhesive to produce a given strain is very much smaller, being about 1 lb for 0·1 per cent strain the case of a typical R.A.E. general purpose design.

Many investigations have been made on the behaviour of different types of adhesive and it is generally agreed that for most work a celluloid base cement such as Durofix gives the best result[42]. For certain applications, however, such as those in the presence of high temperatures it may be necessary to use special types of cement. In cementing the unit to the test surface the latter should be thoroughly clean and free from all grease and the directions of the adhesive manufacturer followed, the minimum of adhesive being used. Care must be taken that the unit is perfectly flat and that no bubbles of air or excess adhesive remain between the surface of the strain unit and the specimen. Ample time must be allowed for the adhesive to set otherwise the full sensitivity of the unit will not be obtained and it will suffer from an apparent hysteresis and lack of reproducibility of results. It has been shown that, for most strain units of this type 24 hours drying is sufficient to give results accurate to within 5 per cent for dynamic work. For static work a somewhat longer interval is necessary. In this connection, when using an adhesive setting by evaporation of a solvent, it is advantageous to use a strain unit whose base is porous, this facilitating evaporation.

This type of strain unit is generally sufficiently flexible to permit of application to curved surfaces. It has a very small mass and because of delicacy in construction the unit is easily damaged before and during installation. After installation, protection from mechanical damage is, therefore, advisable. Protection from moisture is essential if the unit is used in a damp atmosphere, as any moisture absorbed will introduce a low insulation resistance across the connecting leads of the unit and from each of these leads to the test surface. Experience has shown that the best method of waterproofing a wire resistance unit is to cover it and the surrounding surface with a water-proofing compound called ' Di-gell ' marketed by Astor Boisselier and Lawrence Ltd.

5.5. *Pick-ups Incorporating Wire Resistance Strain Units.*—5.5.1. *Load pick-up.*—In many cases load can be determined indirectly from a knowledge of the physical constants of the materials of the structure under test and the strain. Where a direct measure of load is required, *e.g.*, in a cable under tension, a pick-up consisting of a test strip of suitable flexibility, to which is cemented one or more wire resistance strain units, can be used. The design must be such that the unit can be inserted in the structure under test so as to take the load in question. The pick-up is calibrated in terms of load against change in resistance of the strain unit or deflection of the associated recorder. A photograph of a typical test strip of this nature is shown in Fig. 28. The width of the centre portion of the strip to which the unit is cemented has been reduced so that a measurable strain is given by the load to be measured.

5.5.2. *Acceleration pick-up.*—In this type, the strain unit is used to measure the deflection or strain produced in the spring by the action of the acceleration on the mass. Several accelerometers working on this principle have been designed and used successfully. The simplest of these consists merely of a loaded fixed-free cantilever with four strain units arranged so as to measure the bending strain at its root. The four identical strain units are connected so as to form a Wheatstone bridge, two units measuring contraction and two extension when the cantilever bends under the influence of the impressed acceleration. In this way four times the strain sensitivity of a single unit and temperature compensation are obtained. Considerations of size and frequency response limit the application of this particular design.

Another design of strain unit acceleration pick-up is shown in Figs. 29 and 30b. It consists of a thin-walled dural tube, to one end of which is attached an overhanging mass. The other end of the tube is fixed to a heavy metal base. The movement of the mass under the impressed acceleration introduces a corresponding axial strain in the cylinder. This is measured by the four wire resistance units cemented to the tube as shown in Fig. 29. Diametrically opposite units are connected in series and the two pairs of units thus formed connected in the opposite arms of a Wheatstone-bridge network. There is thus partial compensation for bending, the sensitivity to acceleration perpendicular to the axis of the cylinder being less than 10 per cent of the axial sensitivity. The accelerometer can be calibrated statically by the application of known loads along the axis of the tube. The model shown in Fig. 29 was designed to measure accelerations up to $\pm$ 300*g*, the load on the tube at this value causing the mass to move approximately $\pm$ 0·002 in. The natural frequency of the system is approximately 400 c.p.s. and the damping approximately 0·3 critical. Its weight is 1·75 lb.

While these acceleration pick-ups are robust and suitable for the measurement of large accelerations, it is difficult to adapt the design to the measurement of accelerations less than 20*g*. In order to keep the necessary sensitivity the cantilever or cylinder which forms the spring has to be made very flexible and mechanical weakness results. This difficulty has been overcome to a large extent by using the strain unit wires themselves to constrain the accelerometer mass. An accelerometer pick was designed on this principle in 1937 by Gerloff[43]. It consists of a mass supported by fine wires in three mutually perpendicular directions. The mass experiences a force proportional to the acceleration applied and the elastic suspension wires, in turn, experience strain proportional to the force. Thus the acceleration is converted into a corresponding resistance change. The directional components of the acceleration are resolved at the same time as the measurement is made.

A single-axis accelerometer pick-up unit of this type is marketed by the Statham Laboratories, U.S.A. The mass is suspended by four separate sets of strain sensitive wires, under tension. When the mass moves under the influence of acceleration the strain in two of the sets of wires is increased while that in the other two sets is decreased by an equal amount. Each of the four sets of wires form one arm of a Wheatstone bridge. The bridge is connected and permanently balanced inside the instrument. Temperature stability is inherent because of the symmetry of the resistance-bridge arms. A small dry-cell battery is connected to two of the four output terminals, the remaining two being for connection to the recording device. With standard galvanometer recorders both dynamic and static accelerations can be recorded without the use of amplifiers. The accelerometers are oil damped and are manufactured with different sensitivities and natural frequencies so as to cover a wide acceleration range. The model designed to measure accelerations of maximum values of $\pm$ 12*g* has a natural frequency of approximately 270 c.p.s., gives an output of approximately 20 microamps per *g* and has a damping factor of 0·4. Its dimensions are 1·2 × 1·25 × 2·5 in. and its weight is 4 oz. The characteristics of this type of accelerometer are very stable ; effect of change of temperature is negligible, the maximum error if the calibration factor for room temperature is used being + 1·5 per cent of full-scale at + 50 deg C. or — 5 per cent of full-scale at — 50 deg C. An external view of the accelerometer is shown in Fig. 30a.

5.5.3. *Pressure pick-up*.—For the measurement of very high fluid pressures the pressure sensitive property of the wire itself may be used, necessitating only its exposure to the hydrostatic pressure. In its simplest form the pick-up consists of a helically wound coil mounted on a suitable former and protected by insulating varnish from the liquid in which it is immersed.

For measurement of fluid pressures in the range 0 to 5,000 lb/sq in. use is made of the strain sensitivity of the wire, the pressure being made to deflect a diaphragm, the movement of which in turn is either made to strain the wire directly or to strain a gauged elastic member. Statham Laboratories, U.S.A., market a range of pressure units designed on the same principle as their acceleration pick-up, the moving mass of the latter being replaced by a suitable diaphragm. One of these pressure units is designed to measure pressures in the range 0 to 20 lb/sq in. and has a damped natural frequency of 1,000 c.p.s. Another model has a pressure range of 0 to 5,000 lb/sq in. and has a damped natural frequency of 2,000 c.p.s.

Pressure units have been designed in which the movements of a diaphragm strains either a small cantilever or a small ring-type dynamometer. Wire resistance strain-units are attached to the elastic member at points where maximum strain occurs. Where possible it is better to employ four units, one pair experiencing tension and the other pair compression. In this manner the sensitivity is increased and temperature compensation is obtained. Pressure units designed on these lines can be waterproofed and oil-damped.

A simple but effective unit for the measurement of static and dynamic hydrostatic pressure in a pipe line consists of a length of metal pipe of suitable wall thickness fitted with wire resistance strain units so as to measure the resultant strain in the pipe wall. The pipe can be made as a unit, closed at one end so that it can be introduced into the hydraulic system at the desired point. Two strain units are cemented to measure circumferential strains and they form opposite arms of a Wheatstone bridge. Two other similar strain units are cemented to the pipe so as to measure axial strains in the pipe. These form the remaining two arms of the resistance bridge. The difference between the axial and circumferential strains is proportional to the pressure in the pipe, so that the bridge output is proportional to pressure over the working range of the unit. Since the complete resistance bridge is on the pipe there is almost complete temperature compensation. There is also compensation for flexing of the pipe but if its length is kept short this is unlikely to occur.

5.6. *Associated Circuits.*—5.6.1. A suitable associated circuit for the variable resistance pick-up is comparatively simple and may consist of either

(i) A fixed resistance and the strain unit in series forming a potentiometer energised with direct current.

or (ii) A Wheatstone-bridge network energised by either direct or alternating current.

A potentiometer is satisfactory for dynamic work but is unsuitable for the measurement of static or slowly varying strains. When potentiometers are used the effect of the fluctuations in the energising voltage bears no relation to the amplitude of the wanted signal but if a bridge is used these fluctuations result in a definite percentage change in the wanted signal. In general the spurious effect is much greater in the first case and is of particular importance if the energised voltage is derived from a rectified alternating current source. The signal voltage across the potentiometer network is determined by the value of the series resistance, the unit resistance, and the permissible current through it. Maximum sensitivity for maximum permissible current through the unit is obtained when the series resistance is as great as possible. A practical limit to the magnitude of the series resistance is, of course, set by the maximum available voltage. For a given energising voltage maximum sensitivity is obtained when the series resistance and that of the unit are equal and this sensitivity is half of that of the previous case.

5.6.2. *Bridge circuits.*—Bridge circuits are the most satisfactory for general use with variable resistance pick-ups and the remarks of Sections 3 and 4 on bridge circuits for variable inductance and capacitance pick-ups apply equally well here. The sensitivity of the bridge has been considered in some detail by the National Physical Laboratory[42] and by the R.A.E.[41]. In practice, the optimum conditions for a low-impedance recorder and a given strain unit resistance occur when all four arms and recorder resistances are equal, when the sensitivity obtained is half the theoretical maximum. For a given recorder resistance, however, maximum deflection sensitivity is obtained when all four arms are equal and as high as possible assuming the maximum permissible current is passed through the strain unit.

When a high impedance recorder is used, the two ratio arms merely supply a convenient point of constant voltage and the behaviour of the bridge reduces to that of a potentiometer circuit. In practice, a limit is set to the maximum strain unit resistance by thermal effects, insulation resistance between gauge and the earthed test surface and shunt resistance across the strain unit.

5.6.3. *Measurement of steady and slowly varying strains.*—In the simplest method the unit is connected as one arm of a direct current energised Wheatstonebridge network, the out-of-balance current due to the strain being indicated on a sensitive mirror galvanometer. Calibration is effected by varying a small known resistance in series with the strain unit or a large known resistance in parallel with it. A null method of measurement is generally used, the standard variable resistance in series with the strain unit being varied in the opposite sense to the resistance change in the unit so as to keep the resistance bridge on balance.

The above circuit suffices where there is no temperature variation or bending present. Methods of compensation for temperature variation are discussed briefly below. Where bending as well as axial strains are present, two or more of the resistance bridge arms can consist of working or temperature conpensating strain units and by suitable arrangement of the bridge arm either the bending or the axial strains can be cancelled out.

When it is necessary to record the steady strains at a large number of points, particularly if this has to be done in a short interval of time, as is the case during the destructive testing of a test specimen, a mechanical switch is employed. This selects each measuring station in rapid succession, the strain at each point being recorded. 4, 50, 96 and 600-way switching devices have been developed using a cathode-ray tube and camera or pen recorder[44,45]. A combination of the self-balancing bridge system and switching apparatus using a pen recorder, has been developed in the U.S.A. and is marketed by the Baldwin Southwark Co.

5.6.4. *Measurement of dynamic strain.*—The strain unit, associated circuits and recorder must be capable of following faithfully in time and amplitude the different frequency components of the strain under measurement. Frequency limitations are invariably imposed by the associated apparatus and not by the wire resistance strain units. Two basic types of bridge circuits are in general use:—

(i) Direct current energised bridge, the out-of-balance current being passed on to the associated amplifier and recorder. Where response to steady strain is not required, the bridge circuit can be reduced to that of a simple potentiometer as described above, coupling to the associated circuit being done through a suitable condenser.

(ii) Alternating current energised bridge, the change of resistance of the strain unit modulating the carrier voltage which is passed on to the amplifier, phase discriminator and recorder. The advantage of this method is that, where a recorder requiring prior amplification is used, the amplifier, before demodulation, even where response to steady as well as alternating strain is required, need have linear response only over the frequency range covered by the carrier sidebands. In the past the chief disadvantage of this circuit, in its simplest form, has been that the direction of unbalance is not indicated by the polarity of the output current or voltage. This has been overcome by the use of the phase sensitive circuits described in Section 7.

The most suitable type of associated apparatus to use with the bridge for any particular application depends to a large extent on the frequency range over which linear response is required. Subdivided on this basis, the types of precircuits and recorders in general use for strain measurements are described briefly.

Frequency Range: Zero to about 50 *c.p.s.*—Where faithful frequency response is required over the above range only, enough output can frequently be obtained from a direct current energised bridge circuit to operate directly an oscillograph galvanometer.

Frequency Range: Zero to 5,000 *c.p.s.*—Here again it is generally more convenient to use a suitable oscillograph galvanometer of either the D'Arsonval or Duddell type together with a photographic recorder. Due to the higher natural frequency of the galvanometer suspension, however, and consequently the reduced sensitivity, some current amplification is required. If a direct current energised bridge is used this amplifier has to be direct-coupled except for the case where the lower limit of the frequency response is not zero. If an alternating current energised bridge is used the amplifier is alternating current coupled and is followed by a demodulator and phase sensitive circuit, the output being directly coupled to the galvanometer. For work over the frequency range zero to 70 c.p.s. there is now available a direct-writing oscillograph using an electrically charged stylus recording on electrosensitive paper. This recorder is described in Section 10.

Upper limit of Frequency Range: Above 5,000 *c.p.s.*—The associated circuits for use with wire resistance strain-units working at high frequencies consist of voltage amplifiers and cathode-ray oscillographs. Amplifiers with a voltage gain of at least 5,000 are necessary for the cathode-ray oscillographs normally used. If response down to zero frequency is required and a direct current energised bridge is used, then a direct-coupled amplifier is necessary. If an alternating current energised bridge is used the modulated carrier may be recorded or it may be demodulated by a circuit of the phase discriminating type. Either of these circuits, of course, cover the above three frequency ranges. Where response down to zero frequency is not required, it is convenient to use the direct current energised resistance bridge or potentiometer, a suitable alternating current coupled amplifier and cathode-ray oscillograph.

While the strain unit itself introduces no phase errors up to frequencies of the order of 50,000 c.p.s., care has to be taken in the design of connecting leads, bridge, amplifier and recorder circuits so that they do not introduce phase errors. The remarks made in Section 2 on phase errors of acceleration pick-ups apply to galvanometer recorders. Amplifier phase errors are discussed in Section 7.

5.7. *Calibration and Sensitivity of Wire Resistance Strain Units.*—Methods of calibrating the strain unit by subjecting it to known strains either in a test machine, familiar to the materials testing laboratory, or on a symmetrically loaded beam are well known. A calibration for resistance change in the unit against strain is then obtained.

The most straightforward, and usually the most satisfactory, method of calibrating the associated circuits, is to introduce into the bridge arm containing the unit a known change of resistance. Where a null method is used the resistance is varied so as to reduce to zero the deflection caused by the strain under measurement. Where a deflection method is used the known resistance is switched in and out of the circuit so as to simulate a known change of strain in the unit. When a direct current responding circuit is in use this be done slowly, but when the circuit is alternating current responding only, this has to be done rapidly enough to prevent attenuation by the amplifier. The calibrating resistance can take the form of either a low series resistance or high shunt resistance. The latter is better as then the resistances of the switch contacts used to switch the resistances in and out of the circuit are negligible compared with the high shunt resistance. In addition, errors introduced by small changes in the value of the resistance are negligible. In the case where a standard series resistance of the order of one ohm is used both these errors have to be guarded against. Used with a suitable resistance bridge network and passing a maximum permissible value of current through it consistent with the required stability of readings, the wire resistance strain unit will give 10 to 20 mA for a strain of 0·1 per cent when used with a current recorder. When working into a high resistance device, the same strain will give 10 to 20 mV. Using a direct current energised Wheatstone bridge and sensitive recorder, it not difficult to measure a strain of 0·1 per cent with an error not greater than $\pm$ 1 per cent. When measuring strains using an amplifier, robust recorder and a deflection method, the accuracy obtainable is less than for static measurements, but if provision is made for checking the sensitivity of the apparatus frequently it is possible to measure strains of the order of 0·1 per cent with an accuracy of $\pm$ 2 per cent. For smaller values of measured strain the accuracy attainable is correspondingly decreased.

5.8. *Stability of Wire Resistance Unit and Associated Equipment.*—The main source of instability and error is the temperature sensitivity of the strain unit. A change of a few degrees in temperature causes a change in resistance comparable with that given by the strain under measurement. In addition, differential thermal expansion between the unit and the test specimen is recorded even if no stress has resulted from it. Temperature compensation is essential where long term stability is required. This is most conveniently done by the use of a compensating unit, that is, a similar strain unit glued to a bar of the same material and kept at the same temperature. The measuring and compensating units are connected in adjacent arms of the resistance bridge network. Where a pick-up consists of two pairs of strain units working in opposition and connected so as to form a complete Wheatstone-bridge circuit, such as in the Statham accelerometer described in Section 5.5.2, then the unit itself is fully temperature compensated.

A temperature compensated strain unit can be made by constructing it of two lengths of wire of dissimilar materials[46]. These, however, are difficult to design and construct and are compensated only when cemented to a test object having one particular value of coefficient of expansion.

The first method outlined above is used almost universally. Where bending strains are under measurement both 'working' and 'compensating' strain units can often be made to measure strains in opposite senses and thus give twice the sensitivity of a single unit as well as temperature compensation.

Another possible type of instability is that introduced by thermo-electric currents. When the different parts of the bridge circuit, including the strain units, are placed at points at which temperature differences occur, thermo-electric currents may be produced which will disturb the balance of a direct current excited bridge circuit. With care in selection of materials and their arrangement this may be made a negligible source of trouble. Instability may also result from the production of electromotive forces between two dissimilar metals both at the same temperature. This also can be eliminated by careful mechanical design and selection of materials.

For static measurements long term stability is required, but for dynamic work it is not so essential. There may be a continuous change in zero or of sensitivity and yet the accuracy may be high over any particular short period. Under these conditions and in the hands of an experienced operator long term drift may be reduced to no more than a source of annoyance.

6. *Miscellaneous Pick-up Devices and Methods of Calibration.*—6.1. *Introduction.*—In addition to the three basic types of electrical pick-up units described in the foregoing sections, the electromagnetic, electrostatic and resistance, there is a very wide variety of physical phenomena which may be used in pick-up devices for the conversion of a small movement into a proportional electrical effect. The majority of such devices have been used in varying degrees, in instruments required in aeronautical engineering, to supplement the three basic methods. A knowledge of their principles, potentialities and scope of application is of great value to the instrument designer faced with a particular problem. A brief description of the more important miscellaneous devices is therefore given.

6.2. *Piezoelectric Devices.*—The most commonly used piezoelectric materials for mechanical measurements are quartz, tourmaline and Rochelle salt (potassium sodium tartrate). Quartz has the important advantages of high mechanical strength and resistance to heat and moisture, but is about a thousand times less sensitive than Rochelle salt which gives an output of about 0·03 volt per pound for a single crystal. For this reason attempts have been made to overcome the undesirable features of Rochelle salt and it is claimed[52] that the sensitivity and impedance may be stabilised, linearity improved and creep and hysteresis materially reduced.

Quartz crystal pick-up devices have been used widely for the measurement of pressure, in particular for engine cylinder pressures and blast pressures[48,49]. Such devices possess two important characteristics essential for such measurements—a high natural frequency of vibration and insensitivity to temperature changes. With due care pick-ups responding faithfully to sinusoidal variations of 50,000 c.p.s. or higher can be designed. Reliable values of the temperature coefficient of the piezoelectric constant of quartz appear to be unobtainable, but it is fairly well established that it only loses a few per cent of its sensitivity up to about 300 deg C at which temperature it loses almost all its piezoelectric property.

All quartz pressure pick-ups are inevitably subject to errors caused by vibration, the acceleration forces acting directly on the crystals and producing electric charges. One method of reducing such spurious responses is to place the crystal elements in carefully damped mounts[50]. Another interesting method, developed at the R.A.E., is the installation of two similar crystal assemblies in the pick-up, one subjected to the diaphragm pressure, and both equally subjected to vibration, the outputs of the two being combined to balance out the acceleration potentials. Such a device has been used successfully in the R.A.E.–Mullard detonation meter[51].

Other measurements with quartz crystal pick-ups include strain, in which the crystal is cut at right angles to its electric axis, and internal stresses. Their use has been very popular in Germany for the measurement of dynamic loads, transient acceleration and engine cylinder pressures and detonations. Rochelle salt elements, in virtue of their high sensitivity, have found a number of applications such as in vibration pick-up units, incorporating ' twister ' elements inertia coupled to the body under test[52], and in acoustic measuring devices.

A major source of difficulty in the application of piezoelectric pick-ups is electrical leakage which affects the low frequency response of the system. To minimise this and other sources of error, such as changes in cable capacity and insulation, use of a transmission line and mechanical disturbance in the cable[53], it is normal practice to place a condenser in parallel with the unit and increase the amplification to allow for the resulting loss in sensitivity. As a general rule, it may be said that when piezoelectric pick-ups are used for quantitative measurements, great care must be taken in the design and application of the equipment, and frequent and careful checks must be made on its characteristics.

6.3. *Magnetostrictive Devices.*—The permeability of a ferromagnetic material, in particular annealed nickel and some nickel-iron alloys, changes when the material is subjected to mechanical stress. Thus, if a magnetised bar of nickel is stressed, the magnetic flux changes and an electromotive force, proportional to the rate of change of stress, is induced in an encircling winding. This property may therefore be used as the basis of a pick-up and has in particular been used for the measurement of stress and fluid pressure[54].

Magnetostriction devices are sensitive but their sensitivity varies greatly with the composition and heat treatment of the material. Eddy current effects may be avoided by the use of finely laminated material and hysteresis can be reduced by suitable heat treatment, but cannot be entirely eliminated. As magnetic permeability varies with temperature, these devices are unsuitable for use at high and variable temperatures, for example, in internal combustion engines. Their response is roughly proportional to rate of change of pressure. Their mechanical and electrical simplicity is attractive but measurements of precision are not to be expected on account of hysteresis effects.

6.4. *Photoelectric Devices.*—Photoelectric cells are used extensively for the measurement of movement by converting it into a variation of incident light, either by changing the width of a slit or otherwise, and by converting the light intensity in turn into a variation in electrical potential or current. Strain gauges of very short gauge length have been constructed by employing a lever system to transfer the movement to an optical slit or grating which controls the amount of light falling on a photoelectric cell[55,56]. Torsional displacements may be measured in the same way by the use of angular apertures.

The method has also been applied to the measurement of fluid pressures[57]. The pressure is applied to a polished diaphragm, supported around its periphery, on to which a collimated beam of light falls. The divergent reflected beam falls through a slit on to a photoelectric cell and as the diaphragm is deflected the reflected beam becomes more divergent and less light falls on the cell.

When using photoelectric cells quantitatively it is desirable to take measurements in terms of the ratio of light intensities, whenever possible, to avoid errors due to variations in the light source. This can in general be done by using two slits, so arranged mechanically that as one is opened, the other is closed.

6.5. *Hot Wire Devices.*—These devices have been applied mainly as anemometers to the measurement of fluctuations of airspeed in turbulent air flow[58,59] although they have been used for other measurements such as strain and tension[60]. It has been found that the best results are obtained with platinum filaments 0·015 mm diameter and about 5 mm long at operating temperatures of about 200 deg C, this material having a high thermal coefficient of resistance, high resistivity, the required ductility, and is non-corrodible and non-oxidisable.

Thermal elements have in operation several disadvantages. They are less robust and less accurate in use than others and they have inevitably a time lag in their operation. Their upper limit of frequency response depends upon the thermal capacity of the element, and seldom is it higher than a few hundred cycles per second. They are, however, invaluable for some applications in which their exclusive features are desirable, such as in the measurement of the velocities of air in small turbulent patterns.

6.6. *Vibrating Wire Devices.*—In principle, this device consists of a taut steel wire attached to two bridges mounted in such a manner that the strain or other magnitude being measured alters the tension in the wire and therefore its natural frequency. The wire is maintained vibrating at its natural frequency by an electromagnetic method. Normally two gauges are employed, a measuring gauge and a reference gauge, the natural frequency of which is adjustable. The beat frequency between the two gauges is a measure of the strain applied[61 to 64]. This type of gauge has been used successfully in a variety of forms for the measurement of strain, torque and pressure. In Germany the well-known Maihak gauge has been produced commercially and much success in its use is claimed.

6.7. *Vacuum Tube Devices.*—Recently another group of methods of an electronic nature have been applied, mainly in America, to the measurement of mechanical magnitudes, and while still new and not thoroughly developed, show signs of promise. These methods employ electronic valves whose electrode positions relative to each other are controlled by external phenomena. Movement of a particular electrode or electrodes produces a change in the electrode spacing, or in their effective area, which in turn results in a change in the effective resistance. In general, the electrode assembly consists of a cathode and heater, rigidly attached to the valve base, with two flexibly mounted anode plates, one on either side of the cathode. Movement of one of these anodes with respect to the cathode and a similar movement of the other, but in the opposite sense, result in an increase in one anode-cathode impedance and an equal decrease in the other. Thus a push-pull pick-up is produced which can be connected as two adjacent arms in a Wheatstone bridge circuit, and which will, therefore, be relatively insensitive to changes in operating characteristics.

An interesting device on this principle is the electrical micrometer designed by Ross Gunn[65]. Another recent device of interest is the vacuum tube acceleration pick-up made by Sylvania Electrical Products, Inc. The construction is similar to that of a double-diode valve in which the cathode assembly is specially rigid and the two anodes mounted flexibly on supports from the base to have a natural frequency of vibration of about 1,000 c.p.s. The whole electrode assembly is mounted on a ring seal octal type base, the electrode supports being brought out through the glass base to form the contact pins.

The application of acceleration forces to the valve results in a change in the two anode-cathode impedances which form adjacent arms of a Wheatstone bridge network energised by a 20 volt direct current source. Static tests on one of these pick-ups, involving the application of an acceleration of $2g$ by rotating the pick-up through 180 deg ; gave a value for the sensitivity, defined as the ratio of the resistance change for $1g$ to the original resistance of $3{\cdot}37 \times 10^{-3}$. It is of interest to compare this sensitivity figure with that for a wire resistance strain unit for equal movements. From the dynamic characteristics of the accelerometer it is deduced that the movement of one of the anodes for $1g$ is 10^{-5} in.; $\Delta R/R$ for 0·001-in. movement is therefore $3{\cdot}37 \times 10^{-1}$ and $\Delta R/R$ for 0·1 per cent strain in a strain unit is about $2{\cdot}2 \times 10^{-3}$. For equal resistances and currents the valve accelerometer is therefore about 150 times as sensitive as the strain gauge.

Dynamic tests of the pick-up gave a natural frequency of vibration of 950 c.p.s. and a damping coefficient of 0·01. Over the range of applied frequencies of sinusoidal accelerations of 0 to 200 c.p.s. the response to a given acceleration is constant to within five per cent and the maximum phase shift is 14 minutes. The ratio of the response of the pick-up to transverse accelerations, that is, accelerations in a direction perpendicular to the axis, to those along this axis is about 0·1.

Tests carried out by the National Bureau of Standards on a quantity of 49 pick-ups showed that the sensitivity varied from $3{\cdot}7 \times 10^{-3}$ to $7{\cdot}2 \times 10^{-3}$ and the natural frequencies from 295 to 915 c.p.s. It appears therefore that, as the pick-ups are produced at present, individual calibration is essential.

6.8. *Calibrating Devices.*—Owing to the severe conditions under which pick-up units of electrical and electronic measuring systems are used in aeronautical engineering, it is essential for accurate measurement to have accurate calibrating devices which are convenient and reliable in use. These are relatively simple for those pick-ups which may be calibrated under static conditions. Dynamic calibration is more difficult, as is the case when the pick-ups respond to velocity or acceleration, in which case it is necessary to produce a vibratory displacement or strain of known characteristics.

Devices for the static calibration of movement pick-ups, based on the use of the micrometer screw and dial gauge, are well known and need not be discussed. For the static calibration of strain gauges of the resistance-wire type devices incorporating elastic stressed members are used, the two general types being those experiencing direct or axial strain and those strained in flexure. An example of the former type is the Olsen machine familiar in the mechanical testing laboratory. In the latter type, the best method is to use a beam of rectangular cross-section of high-strength steel symmetrically supported at two points and symmetrically loaded at its ends. In this way, the bending moment, and therefore the strain, along the beam is constant between the two supports and its value may be computed from the dimensions of the beam, spacing of its supports, the Young's modulus of its material, and the loads applied.

When a dynamic calibration is desired, *e.g.*, to calibrate a system employing a resistance-capacity coupled amplifier, it is in general more convenient to compute the strain in terms of deflection. One method is to employ a cantilever deflected cylindrically by a ball-bearing mounted actuating cam driven by an electric motor.

As a rule the greatest source of error in the use of elastic members as calibrating devices is in the evaluation of the Young's modulus of the material. Another source of error arises in the use of a dynamic calibrator due to the vibratory strain which may be introduced by the inertia effects of the rapidly moving parts. These inertia effects increase rapidly with increasing frequency.

The most accurate device for the static calibration of pressure and load pick-ups is the dead-weight calibrator. This consists essentially of a piston of known area upon which known weights can be placed in order to produce a known fluid pressure, frictional errors being reduced by rotating the piston during the test. For the production of relatively low pressures for calibrating purposes, the water or mercury U-tube manometer is more convenient. Bourdon gauges of sufficient accuracy are also now available to serve as secondary standard.

For dynamic calibration of pressure pick-ups the balanced diaphragm indicator, which indicates equality of pressure, may be used. This consists of two pressure chambers separated by a diaphragm. A known pressure is maintained on one side of the diaphragm, and electrical contacts are made by deflection of the diaphragm each time the fluctuating pressure, applied to the other side, exceeds the known pressure. There are two sources of error in this type of instrument, one due to the pressure difference required to move the diaphragm and the other due to the inertia of the diaphragm. As a result of the latter effect, a pressure pulse of sufficiently short duration may not cause the diaphragm to move even though its peak value may be greater than the reference pressure. Also of importance in this and other types of pressure units is the effect of inertia and viscosity on the gas whose fluctuating pressure is to be measured. If the passages within the unit are too constricted the pressure there will not always be equal to that in the chamber where the measurement is required. It is also possible for resonant vibration to be set up in these passages.

Another interesting device for dynamic calibration of pressure gauges is the pistonphone which consists essentially of a piston and cylinder, of known dimensions, and an electric motor to move the piston. The variation of pressure within the cylinder may be computed for any piston position, assuming a constant temperature. It is difficult with this method to obtain a truly sinusoidal pressure fluctuation and corrections for temperature effects are involved. These are fully discussed in standard works on acoustics.

Instruments for measuring the components of vibration, especially acceleration, require greater care in calibration than almost all others. Whether the pick-up is amplitude, velocity or acceleration responding it is necessary to produce a sinusoidal vibration of known adjustable amplitudes and frequencies, the low frequencies being the most important for seismic systems and the higher frequencies for acceleration pick-ups, in order to determine the performance of the unit. These vibrating tables are usually operated by mechanical, magnetic or piezoelectric driving units.

A mechanically driven table may be either the direct drive type or the reaction type. The former employs a cam or an eccentric to convert the rotary motion of a motor to linear simple harmonic motion. The reaction type employs a rotating unbalanced mass running in bearings attached to a spring suspended table, the unbalanced forces produced causing the entire assembly to vibrate. The frequency of both types is controlled by the speed of the driving motor. The direct drive mechanism has the advantage that the amplitude of vibration is easily and accurately controlled by adjusting the throw of the eccentric. With this method, it is also possible to produce a more accurate simple harmonic motion by employing two eccentrics with connecting rods, with their outputs so connected that the two harmonics of the sinusoidal motions oppose and counteract each other. The reaction type is simpler in construction, but it is less easy to adjust and the amplitude is not accurately known unless specifically measured. It has the advantage that no appreciable vibration of the frequency of the table is transmitted through the base of the calibrator to the structure on which it is resting.

An example of the direct drive type is the Sperry-M.I.T.* calibrator for linear and torsional vibration pick-ups. In this table, the linear vibration impulser consists of a spring loaded follower, driven by an adjustable eccentric on the fly-wheel shaft. The double amplitude of vibration is adjustable from zero to 0·1 in. and the frequency from 4 to 90 c.p.s. by means of a variable speed link-belt transmission unit. The spring tension on the follower is sufficient to vibrate a 6 lb mass at 50 c.p.s. The torsional vibration impulser consists of a shaft which is driven from the fly-wheel through a universal joint, the magnitude of the torsional vibration being determined by the angle at which the universal joint is set and a range from 0 deg to 1·5 deg double amplitude being provided at frequencies from 8 to 180 c.p.s.

The Miller Model 9B calibrator is a typical example of the reaction type in which vertical, horizontal and torsional tables are all driven by the reaction of adjustable, rotating eccentrics.

* Massachussetts Institute of Technology.

The natural frequency of the suspended system is less than 5 c.p.s. and the working range of frequencies is from about 5 to 60 c.p.s. Over this range, the amplitude for a given setting does not vary by more than a few per cent and its maximum peak to peak range for the linear table is about $\frac{3}{8}$ in. and for the torsional table about 7 deg. The maximum weight loading allows the use of several pounds on each table. Optical indicators, actuated through fluid drives, are provided to show the approximate amplitudes of the vibrating tables.

Piezoelectric driving units are normally applied to the production of small amplitude vibrations of high frequency. 'Expander' type crystals are generally used and vibrations at frequencies as high as 20,000 c.p.s. may be produced, mechanical resonances in the crystal mountings giving rise to trouble when much higher frequencies are attempted.

Magnetic drive tables usually employ the principle of mechanical resonance in order to provide greater amplitude. One form, designed by Greentree[66], consists in principle of an elastically supported coil positioned in a magnetic field. The coil is made to vibrate at the desired frequency by passing an alternating current of the required frequency through it, and adjusting the spring supports until resonance occurs. Another method makes use of an appropriately excited, self-maintained cantilever beam. This type may be used for the calibration of both vibration pick-ups and strain gauges. For the calibration of velocity or acceleration pick-ups using vibrating tables and computing the applied velocity and acceleration from the amplitude and frequency of vibration it is important that the degree of harmonic in the applied vibration be as small as possible. For this work, therefore, tables operating at mechanical resonance, are in general to be preferred.

6.9. *Calibration Check of Associated Equipment.*—In the foregoing section the calibration of the pick-up with or without its associated circuit and recorder has been discussed. In addition, it is desirable to have a calibration check circuit to afford an immediate and convenient frequent check on the sensitivity of the associated circuits and recorder. The most straightforward and satisfactory calibration checking circuit is that which produces a change in the same circuit parameter as does the pick-up unit itself. This is in most cases possible with variable capacity, inductance and resistance systems, especially if the system responds to static effects. Due care must, however, be taken with a number of spurious effects since the injected signal is in general of such a small magnitude. The effect of contact resistance must be reduced to a negligible value, for instance, when injecting resistance signals ; thus the method involving a change in a high shunt resistance is superior to that involving a change in a series resistance. In the case of alternating current energised systems, the effect of stray capacity and inductance must also be eliminated.

Should the straightforward method of applying calibration check signals prove impracticable, it is advisable to inject voltage signals of known amplitude, and sometimes known frequency, into the circuit. This method is employed in the six-channel recorder described in Section 10, the signal being injected automatically immediately prior to each measurement.

7. *Amplification of Pick-up Outputs.*—7.1. *General Requirements.*—The signal developed by the pick-up unit and its associated precircuit is in general of low voltage and very low power. To permit this signal to operate an oscilloscope it has to be amplified, and the essential requirement of the amplifier is that it should give an output voltage or current that is an exact replica on a bigger scale of the input voltage. As the design of an amplifier is very dependent on the type of pick-up with which it is to be employed, the type of oscilloscope that it has to operate, and the range of frequencies present in the output from the pick-up and precircuit, it is not possible to cover all requirements with one design. The degree of amplification required is also dependent on these factors, but, as a typical example, a voltage amplification of approximately ten thousand is required to amplify the output from a 2000 ohm wire resistance gauge carrying its maximum safe current, to produce 2 in. deflection for a strain of 0·02 per cent on a cathode-ray tube with a final anode voltage of 1,200. This degree of amplification is somewhat greater than that demanded when a cathode-ray tube is used under comparable circumstances with an

electromagnetic generator type vibration pick-up and integrating circuit. This type of pick-up gives an output of the order one volt per inch per second.

The whole gamut of frequencies to be dealt with in measurements in aeronautical engineering extends from static conditions continuously to about 20,000 c.p.s., the present-day tendency, being for the higher limit to increase to the region of 100,000 c.p.s. The relevant part of this wide-frequency spectrum is determined by the particular application, the low-frequency end being frequently of great importance. For flight equipment it is found more satisfactory and economical to subdivide the general frequency range into three categories :—

(i) 20 to 20,000 c.p.s.

(ii) 1 or 2 to 1,000 c.p.s.

(iii) 0 to 100 c.p.s.

In the case of equipment used for ground tests, however, it is generally possible to design one instrument to cover the complete range. Complete amplifiers in each of these categories will be discussed later in this section. As the input and output circuits employed are, in general, independent of the frequency range covered by the amplifier, and depend mainly on the type of pick-up and oscilloscope being used, these will be discussed first.

7.2. *Input Circuits*.—When the amplifier is fed from a low-impedance source, such as an electromagnetic generator pick-up or a bridge circuit for use with resistance gauges, the input circuit may consist merely of a coupling condenser and attenuator of resistance 1 megohm or less, the only proviso being that the time-constant is adequate for the lowest frequency to be handled. When a high-impedance pick-up, such as a piezoelectric type, is used the input impedance of the amplifier must also be high, both to avoid excessive loss of signal voltage across the pick-up itself, and to attain a satisfactory time-constant in the input circuit. Most normal amplifying valves suffer from serious ' grid-blocking ' if a grid leak exceeding two megohms is used. This may be overcome to some extent by using a lower filament or heater voltage than the rated value. Another method is provided by the electrometer triode valve. This valve is designed so as to have a very high grid-cathode resistance, and to operate with low filament and anode voltages. Owing to the large spacing between the grid and cathode the gain obtainable is low, and to make full use of its characteristics it should be used in a light-tight box in dried air. This makes it somewhat unsuitable for work in other than good laboratory conditions. A satisfactory method for obtaining high input impedance results from the use of a normal amplifying valve connected as a cathode-follower. If two resistances R_2 and R_3 are connected in the cathode circuit of the valve, R_2 being connected to the cathode and their junction back to the grid through a resistance R_1, the effective input impedance is

$$\frac{R_1[1 + g_m(R_2 + R_3)]}{1 + g_m R_2}$$

where g_m is the mutual conductance of the valve.

This can be made much higher than the resistance of the grid leak R_1, if R_3 is high compared with R_2. If variable attenuation is required the output voltage may be taken from tappings on R_3, or from a tapped grid leak in the next stage. The stage gain of a cathode follower is always less than unity.

7.3. *Output Circuits*.—The choice of output circuit is decided primarily by the type of oscilloscope—whether galvanometer or cathode-ray tube is to be used—and also by the frequency range to be covered. For galvanometers the obvious, but not always the best, method is to use the primary of a step-down transformer as the load in the output stage, the ratio being suitable to match the valve impedance to the galvanometer impedance. If push-pull output stages are used a centre-tapped primary is required, one end of the primary winding going to each anode and the centre-tap to the high-tension line. This method is used in the Sperry-M.I.T. Vibration recorder mentioned in Section 10. Its advantages are :—

(i) No direct current flows through the galvanometer so that the zero does not require frequent adjustment.

(ii) The impedance matching means that almost all the power of the output stage is transferred to the galvanometer.

The use of the transformer is not advisable at low frequencies as a large phase shift, increasing with decrease of frequency, is introduced. This method cannot be used if direct coupling is necessary.

To overcome this limitation the low output impedance of a cathode follower is taken advantage of, the galvanometer being direct coupled in the cathode circuit. This method is employed in the R.A.E. six channel electronic recorder for flight use described in Section 10, the circuit of the amplifier being shown in Fig. 31. The circuit results in a large wastage of power if low-resistance high-current galvanometers are used. This wastage is less if high-resistance, low-current centre-tapped galvanometers are employed, each half of the coil winding forming the cathode load of one valve. The method introduces no phase shift, and, even if a large amount of power is wasted, is superior at low frequencies to transformer coupling.

Owing to the high impedance it presents to the amplifier, to which the impedance of a voltage amplifying valve is comparatively low, the cathode-ray tube may be merely direct or resistance-capacity coupled to the last amplifying valve. At high frequencies the capacity of the tube electrodes (50 to 100 micro-microfarads) and connecting lead from amplifier output to tube may cause a fall in response. To minimise this the connecting lead should be as short as possible and of low capacity cable, and the anode load of the output valve or valves should be kept as small as possible. Any residual drop in response at high frequencies may be compensated by connecting a suitable condenser in parallel with the cathode load of an unbalanced amplifying stage.

The sensitivity of a cathode-ray tube may be expressed as X/V_a mm per volt where V_a is the final anode voltage. The voltage required for full screen deflection tends to be fairly constant for a fixed V_a, irrespective of the screen size. This is because small tubes are in general shorter so that the angular deflection required tends to remain constant. A widely used tube for photographic recording, Type No. VCR. 529, requires 100 volts direct current for full screen deflection at a final anode voltage of 1,000, and any amplifier used with the tube under these conditions should give an undistorted peak to peak output of at least 100 volts.

It is always advantageous to use push-pull amplification in the output stages of any amplifier used in conjunction with a cathode-ray tube. The advantages are :—

(a) Each valve has to provide only half the output voltage that would be required from an asymmetric stage. This results in a reduction of distortion.

(b) The deflection of the cathode-ray tube's spot is symmetric. This prevents trapezium distortion which would result in a variation of the deflection sensitivity with change of spot position, and change of focus of the spot with position.

(c) The current drain from the power pack supplying the amplifier tends to remain constant.

If push-pull output is used phase splitting within the amplifier is necessary if the pick-up potential is unbalanced with respect to earth. The methods which may be employed are :—

(i) *Paraphase method.*—This system is shown in Fig. 32a. The valve V_2 is fed from the output of V_1 by the potentiometer R_1, which is adjusted until the signal voltage between grid and cathode of V_2 is equal and opposite to that of V_1. The method is suitable for both alternating and direct current amplifiers.

(ii) *Single valve phase splitter with equal anode and cathode loads.*—In Fig. 32b the valve has equal anode and cathode loads, so that the signals across these loads are equal and can be connected to subsequent stages so as to be in opposite phase. The method is not recommended for use with direct current amplification, owing to the difference between the steady potentials at the anode and cathode. Also, there is a high direct current voltage between cathode and heater of the valve.

(iii) *Constant potential grid method.*—Another circuit for phase splitting is that shown in Fig. 32c. The grid of V_2 is kept at a fixed potential, while the asymmetric signal voltage is applied between the grid of V_1 and earth. The valve, V_2, experiences a corresponding change of voltage on its cathode, so that the signals on the two anodes are in opposite phse. It is obvious that these two signals cannot be quite equal in magnitude, as there would then be no signal voltage across R_k and V_2 would experience no grid-cathode signal. It can be shown that, neglecting the effect of anode load and screen characteristics, the ratio of the signal voltage at the anode of V_2 to that of V_1 is $(1 + R_k g_m)/R_k g_m)$. To make this nearly equal to unity both R_k and g_m must be high, for example, if $R_k = 1{,}000$ ohms, and $g_m = 8{\cdot}0$ milliamps per volt, the ratio is 9 to 8, while if $R_k = 500$ ohms and $g_m = 2{\cdot}0$ milliamps per volt it is 2 to 1. It should be noted that if the unequal signals are fed to two further valves with common cathode load further equalisation occurs, and in the cases quoted the final out-of-balance can be made as small as 1 per cent.

(iv) *Centre-tapped transformer.*—A method of phase splitting common in radio practice is to pass the asymmetric signal through the primary of a transformer, the centre-tap of the secondary being earthed, and the grid of each push-pull valve being connected to one end of the secondary (Fig. 32d). The method is attractive in its simplicity, but, except for use in carrier circuits required to pass a limited band of frequencies, the design of a suitable transformer with reasonable phase characteristics for quantitative work is practically impossible for work at very low frequencies.

7.4. *Amplifier with Frequency Range* 20 *to* 20,000 *c.p.s.*—The range 20 to 20,000 c.p.s. presents the least difficulty in design. Normal resistance-capacity coupling circuits may be employed, and their time constants need not be long. The use of inductive and tuned circuits is not recommended in amplifiers for engineering investigations, owing to the difficulty of attaining constant response over a wide frequency range, and maintaining constancy over a wide range of temperature. At the higher end of the range some falling off in response may be present owing to stray capacities, which should be kept to a minimum. The response may be improved at this end by using a small condenser across the bias resistance in an unbalanced stage. No difficulty is experienced in keeping the phase shift in the amplifier to a negligible amount. The accuracy of measurement in this frequency range is, in general, set by the pick-up connecting cables and the upper limit of recording speed, rather than by the electronic circuits. The other two ranges are more difficult to satisfy and are discussed in some detail in the following sections.

7.5. *Amplifier with Frequency Range* 1 *or* 2 *to* 1,000 *c.p.s.*—The range 1 or 2 to 1,000 c.p.s. also permits resistance-capacity coupling, but the time constants have to be long to enable the required low-frequency response to be attained. If only one coupling circuit is necessary this does not lead to any disadvantages, but, if the gain required necessitates the use of several stages, with correspondingly more coupling circuits, the amplifier tends to 'paralyse' when switched on, and has a long settling down time, both in this case, and if the amplifier is momentarily overloaded. The phase shift (the sum of $\tan^{-1}(1/\omega CR)$ for the stages) tends to increase as the frequency is reduced.

7.6. *Direct Coupled Amplifier.*—When it is essential to amplify signals of very low frequency one of two methods may be adopted. The signal may be amplified at its own frequency by means of a direct coupled amplifier, or it can be used to modulate a high-frequency carrier, which may subsequently be amplified by means of a condenser coupled amplifier. The latter method is discussed in Section 7.7.

The design of a stable direct coupled amplifier is much more difficult than that of a condenser coupled type of comparable gain and the difficulties are greater the higher the gain required. The use of direct coupling between stages introduces drift due to thermal effects in resistors, and any long term variations in anode and heater potentials due to mains variations are passed on in amplified form through the amplifier. If the anode of one valve is coupled directly to the grid of the next, this grid will be at high potential compared with that of the cathode of the first valve. To ensure that the effective grid bias of the second valve is correct, its cathode must also be raised to a positive potential nearly equal to the grid potential. If several stages are required to produce sufficient gain, the high-tension voltage must be high, and, in addition, the potentials between cathode and heater become excessive in the later stages. This system of coupling, however, is quite satisfactory if only two or three stages of amplification are required.

If symmetric deflection is necessary, the paraphase system of phase splitting is satisfactory. The circuit of a low-gain amplifier of this type is shown in Fig. 32a. Two high-slope pentode valves are used to form a single paraphase stage giving a gain of approximately 300. Matched valves are employed, and the unity gain potentiometer between them is adjusted to obtain equal amplifications from the two valves. The meter connected across part of the two anode loads indicates whether the shift control is so adjusted that the anode potentials with respect to earth are equal, so that the spot is at the centre of the cathode-ray tube screen. Owing to the low gain and the use of a single stage with stabilised high-tension supplies, the drift is negligibly small.

When high gains of the order of 50,000 or more are required the difficulty, mentioned above, of obtaining the correct operating potentials on the valve electrodes becomes serious. One method of overcoming this is to connect a dry battery between each pair of stages to ' back off ' the excess voltage between anode and grid. This is undesirable in an amplifier obtaining its high-tension supplies from a mains driven power pack and, in any case, the capacities of the batteries to earth result in a loss of amplification at high frequencies. A gas discharge tube may be used instead to reduce the voltage by the requisite amount[67]. Miller[68] has developed a circuit having a gain of over 100,000 employing this method. Other features of this amplifier are highly stabilised high- and low-tension supplies, and the control of gain by change of negative feedback.

A symmetric direct coupled circuit giving an amplification of 20,000 has been developed by Cinema-Television in conjunction with R.A.E. for the Six Channel Electronic Recorder for Ground Use (Mark 1). The circuit is shown in Fig. 33. The constant potential grid method of phase splitting is used, and the grids of the second stage are at the potentials of the anodes of the first stage. The gain is controlled by varying the amount of negative feedback. Alternative integrating circuits may be switched in when required. The high- and low-tension supplies are both stabilised, and the circuit of the power pack for the former, employing hard valve stabilisation is also shown. Long term stability is good, no appreciable change of spot position on the cathode-ray tube occurring over a period of an hour.

Another symmetric direct coupled amplifier has been developed by the Plessey Co. to R.A.E. requirements. The circuit is shown in Fig. 34. The constant potential grid method of phase splitting is employed in the initial stage, compensation being obtained in the subsequent stages for the residual unbalance in this stage. The cathodes are at progressively higher potentials with respect to earth. The maximum gain is 10,000. Normal potentiometer attenuation is used both at the input and before the ultimate stage, the two potentiometers being ganged. The alternating current mains voltage is applied to a constant voltage transformer, to stabilise, to some extent, both low- and high-tension supplies. The heaters of the first valves are supplied with rectified alternating current to minimise heater ripple in the amplifier. The high-tension supply is further stabilised by means of gas-filled tubes.

7.7. *Carrier Method.*—A method of working down to zero frequency without the use of a direct coupled amplifier is to employ a carrier technique. The pick-up signal is used to amplitude-modulate a carrier, of frequency at least five times that of the highest frequency to be recorded. The amplifier has then to pass, without distortion, a range of frequencies defined by the side-bands. The simplest method is to apply the modulated wave directly to the oscilloscope, using the double amplitude of the modulated carrier for measurement. It is necessary that the carrier voltage shall be constant, as fluctuations in carrier amplitude produce corresponding fluctuations in the output voltage. This method has two disadvantages—the first that the oscilloscope must respond to the carrier frequency, whereas the modulation is of much lower frequency, and the second that if the modulating signal varies in both positive and negative directions with respect to the working level the initial amplitude of the carrier output from the precircuit must be adjusted to permit the whole signal to produce modulation from slightly greater than 0 per cent to slightly less than 100 per cent. Often, trial records are necessary before the correct conditions are found.

These disadvantages are overcome by the use of a phase discriminating demodulator, and this system is used in the R.A.E. six channel amplifier Type IT1-1. The demodulator consists of a double-diode connected as shown in Fig. 35, which also shows the complete circuit for one amplifier. 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 output voltage is in the correct sense with respect to the zero. The demodulator cancels a small degree of output voltage due to reactive unbalance in the bridge, so that the bridge need not be exactly balanced reactively. The system is arranged for use with either inductance pick-ups or wire resistance strain gauges, and the out-of-balance voltage is amplified and applied to the oscillograph galvanometer via the demodulator. The carrier frequency is 2,000 c.p.s.

7.8. *Power Supplies for Amplifiers.*—Although batteries made up of primary or secondary cells provide a constant power supply having a comparatively low internal impedance, their use is rarely convenient owing to their limited life. As 200 to 250 volt, 50 cycles alternating current mains are generally available in this country, equipment for ground use is usually designed to operate from them. For amplifiers, high tension voltages of the order 500 volts are required to obtain sufficient undistorted amplitude of output voltage. The voltage at the mains input terminals of a piece of equipment is rarely constant, and variations may be divided into two classes, slow, long term changes of voltage over several minutes and transient changes produced either by operation of electrical equipment in close proximity to the equipment or in the equipment itself, for example, by operation of the camera drive motor.

Variations in mains voltage can produce two effects—a spurious deflection on the oscilloscope, and a change in gain of the amplifier owing to reduced low- and high-tension voltages. When condenser coupled amplifiers are used the former effect is, in general, not encountered, as the variations are too slow to be passed by the coupling circuits. The second effect may be overcome by soft valve stabilisation and employment of negative feedback to render the amplifier gain less dependent on any residual high-tension voltage variations. Long term voltage variations are more serious when direct coupled amplifiers are used. Constant voltage transformers may be used, together with a high degree of electronic stabilisation. In some cases gasfilled stabilising tubes are sufficient, but in others, especially when the amplifier gain is high, hard valve stabilisation or a combination of hard valves and gas filled tubes must be used. In all cases, and particularly when multi-channel recording equipment is being used, the internal impedance of the high-tension source must be as low as possible to avoid fluctuations of high tension voltage with changes of high-tension current. Heater voltages are obtained from the mains by means of a step-down transformer and may then be rectified, if necessary.

As alternating current sources are not normally available in aircraft, the primary source of current for general flight equipment is the 12 or 24 volt aircraft battery. To adapt ground equipment for flight use a rotary converter, providing 200 to 250 volt, 50 cycle alternating current may be used. This method is inefficient owing to the double conversion involved, and in equipment designed especially for flight use a double commutator rotary converter, or direct current transformer, producing a high voltage direct current from a 12 or 24 volt direct current input, is used. The output voltage is then dependent on the input voltage, but hard valve or gas filled tubes may be used for stabilisation, as in the ground equipment. Inductance-capacity filters are used to prevent commutator ripple entering the amplifier or being produced across the primary battery and interfering with other equipments running from it. Heater voltages are obtained direct from the battery, the heaters being wired in series, parallel or series-parallel to eliminate or minimise power wastage in voltage dropping resistors.

7.9. *Distortion in Amplifiers.*—The requirement that an amplifier shall give an output voltage or current which is an exact replica on a larger scale of the input voltage necessitates consideration of the types of distortion which may be introduced by an amplifier. There are four types[69] :—

(i) Attenuation distortion, or the variation of overall gain with frequency.

(ii) Harmonic distortion, or the introduction by the amplifier of frequencies harmonically related to the input frequencies.

(iii) Phase distortion, or a variation in the time delay of individual input frequencies in such a way as to produce a phase shift between the output of these frequencies.

(iv) Transient distortion.

Methods of minimising attenuation distortion have already been discussed. Harmonic distortion may easily be kept well below 5 per cent by using class A stages throughout. The use of classes AB, B or C amplification is not suitable for amplifiers for quantitative work. Transient distortion is rarely encountered in resistance-capacity coupled amplifiers, and if it does arise is due to stray inductive effects. It may be removed by careful attention to the disposition of wiring and the use of non-inductive resistances and capacitors.

Phase distortion is of particular importance in the work discussed in this report. The requirement that the form of the signal at the output terminals shall be identical with that at the input is satisfied both by zero phase-shift and a phase angle between output and input proportional to frequency (constant time delay at all frequencies). Even if the condition of constant time delay could be attained there would still be an error in interpreting records if instantaneous marks corresponding to an external event (for example, the attaining of a particular piston position in a reciprocating engine) were applied, as the record would be displaced along the time axis with respect to these. However, in a resistance-capacity coupled amplifier the phase angle is an inverse function of frequency, being $N \tan^{-1} (1/\omega CR)$ where N is the number of stages of equal time constant CR.

The only practical solution is to design so that the phase shift is negligible, by using long or infinite time constants and by using negative feedback over two or more stages (it should be noted that feedback by cathode degeneration, *i.e.*, indecoupled bias resistors, does not improve the phase characteristics). The use of negative feedback is always advisable as it improves all forms of distortion, and also makes the amplifier very much less sensitive to variations in characteristics from valve to valve. Its only disadvantage is the reduction in gain that it entails, and this has to be overcome by increasing the number of stages of amplification. This necessitates a compromise, as the greater the number of coupling circuits, the greater is the phase shift and the ' settling down time ' after switching on or overloading.

7.10 *Further Considerations in Amplifier Design.*—An effect that can give rise to a large amount of trouble with spurious signals is low-frequency radiation from alternating current leads in proximity to the amplifier, owing to electromagnetic radiation. This can be minimised by careful screening of the amplifier chassis and case and of the input leads. The screens and the metallic surface to which the pick-up is attached are connected to earth. Mains ripple is also sometimes introduced if all the valve heaters are operated from alternating current. If this is due to magnetic effects a centre tapped resistance across the heater supply with the centre tap earthed, or an earth on the centre tap on the secondary of the heater transformer will remove it, but if due to fluctuations in cathode temperature due to low thermal inertia the effect can be removed by feeding the heaters of the early stages from a direct current source.

It should be noted that these effects cannot in general be removed by filtering, as the amplifier has to handle signal voltages at 50 c.p.s. On account of this, spurious signals at this frequency are particularly troublesome.

7.11. *Future Trends of Amplifier Design.*—Despite the rapid progress of electronic techniques for mechanical measurement, and in the development of amplifiers especially for this purpose, amplifier design for quantitative measurement can by no means be regarded as satisfactory. Owing to the stringent requirements of response, stability and accuracy, development along lines different from those of the more orthodox radio receiver amplifier is required, although improved design in the latter can frequently be adapted. The following are some of the points to which it is considered that attention should be given :—

(i) The use of symmetric (push-pull) amplification from input to output. This will facilitate the use of pick-ups giving symmetric output voltages with their inherent advantages over unsymmetrical pick-ups.

(ii) The increased use of carrier techniques.

(iii) The development of more stable direct coupled amplifiers, capable of being used under flight conditions.

(iv) The increased employment of negative feedback, particularly for gain control, with its advantages of lower distortion and reduction of spurious effects, in the same ratio as the signal gain is reduced.

(v) The use of miniature valves and components for making light, compact flight equipment. Reliable, compact components such as attenuator stud-switches are not available in Britain, but American manufacturers of electronic equipment for use in flight employ them extensively with advantage.

(vi) The reduction of amplifier microphony due to the effect of the severe flight and test-bed conditions on valves and components.

7.12. *Mechanical and Electronic Switching.*—To enable a number of pick-up signals to be handled either by one amplifier and one oscilloscope, or by one oscilloscope after individual amplification, mechanical or electronic switching may be employed. A single amplifier and oscilloscope with several precircuits, or, alternatively, a single oscilloscope, with several pre-circuits and amplifiers, may be used for obtaining phased multi-channel records. The input of the amplifier in the first case, or of the oscilloscope in the second, is switched in rapid succession to the individual precircuits or amplifier outputs respectively. The record consists of a series of envelopes of square waves, individual envelopes being displaced with respect to each other by the application of various steady voltages, so that the traces corresponding to the channels are suitable separated.

The principle is the same whether mechanical or electronic switching methods are used, the two methods differing in the maximum signal frequency that they will handle. If separate amplifiers are employed the signals being switched are very much larger than those which have to be handled if a single amplifier is used. The effect of spurious signals, for example those produced by contact potentials in a mechanical switch, is very much less serious in the former case.

If mechanical switching imposes no frequency limit in a particular application the most satisfactory method is to employ either a motor driven commutator switch, which will produce a total switching frequency of up to 1,000 per sec, or a motor driven Post Office selector switch, which will operate at a maximum switching frequency of 100 per sec on each channel.

The principle of the electronic switching method is that a series of valves are triggered in sequence by pulses derived from an oscillator. The output voltage from each pre-circuit or amplifier is connected to the amplifier or oscilloscope only when its associated valve is conducting. As in the case of mechanical switching, the steady potentials may be adjusted to give separation of the traces. The input and output pulses of the switch must be of square wave-form and this limits the maximum switching frequency obtainable. This frequency can be made 10,000 per sec fairly easily, and 50,000 per sec is generally considered to be the practical upper limit of total switching frequency.

The maximum recordable frequency for both methods of switching is easily calculable. If n channels are each switched x times per sec, the maximum frequency that may be recorded on any channel is approximately $(x/5)$ c.p.s. and the total switching frequency is nx. If six channels are required and a mechanical switch with a total switching frequency of 1,000 per sec is used, the maximum recordable frequency is about 30 c.p.s. If an electronic switch were used, and were capable of a total switching frequency of 25,000 per sec, the maximum recordable frequency would be 750 c.p.s.

The advantages of the switching method of multi-channel recording are the economy and compactness of a single oscilloscope with its attendant advantages of simplicity of optical and mechanical design for photographic or pen recording. If individual amplifiers are used there is an economy of electronic circuits, though this is counter-balanced partly or wholly by the switching circuit, if this is electronic. Its disadvantages are the limited range of frequencies that can be recorded and the extreme care necessary to avoid interaction between the channels. There is also the risk of failing to record a transient effect occurring at a pick-up as, during that period, the particular channel concerned may be inoperative.

8. *Methods of Recording.*—8.1. *Introduction.*—Three types of component, whose operation is based on different physical principles, have been used to record the output from a pick-up unit after the requisite amplification. These are the cathode-ray tube, piezoelectric galvanometer and the electromagnetic vibration galvanometer. The first is now so widely known and applied that it needs no consideration here. Its relevant characteristics when applied to the measurement of mechanical quantities have been referred to in the appropriate sections. Vibration galvanometers of the electromagnetic type are of more limited application, but have been found of great value for the class of measurement described in the present work. They are therefore discussed in some detail later. Galvanometers employing a piezo-electric crystal as the electromechanical converting unit are also used. Voltages applied to the crystal produce corresponding torsional vibrations which are made to deflect a light beam reflected from a mirror attached to the crystal. Both types of vibration galvanometer are more compact than cathode-ray tubes, but are less robust, more expensive and have a narrower useful frequency range. The low impedance of the electro-magnetic type leads to difficulties in the amplifier design. It is more satisfactory to employ cathode-ray tubes except in cases in which their size precludes their use.

The methods of producing the actual traces from the above or, more directly, from the pick-up itself, fall into two general classes :—

(i) Photographic method.

(ii) Direct method with pen, stylus or indentation.

Undoubtedly the clearest and most convenient type of record is that produced photographically and the method will be described in some detail in subsequent paragraphs. Recorders using direct inking methods, leaded paper, waxed paper and celluloid strip with scratch or indentation suffer from a number of disadvantages, the major one being their comparatively low limit of frequency response. This limitation is inherent in the method, due to the large inertia of the moving element and the friction of the recording point on the recording material.

Electrical markers, producing either a perforated trace by discharge through thin paper or a violet trace on iodised paper, require less friction between the recording point and paper for satisfactory operation and can frequently be used at comparatively high frequencies. Teledeltos paper is the most recent recording material of this class. This is a thin paper with a conducting backing which gives a dark trace when a high voltage spark passes between its surface and the backing.

Sound recording techniques have recently been applied to a limited extent to the recording of physical quantities. Both the photographic method[70,71,72] producing a variable-area type track, and the magnetic tape method[73], have been applied with some success, the records being played back for normal recording or for analysis in a suitable vibration analyser.

8.2. *Electro-magnetic Vibration Galvanometers*[74].—8.2.1. *Types*.—These may be classified as coil and bifilar types. The coil type is made up of a small rectangular or circular coil suspended in a magnetic field, whose direction is parallel to the undisplaced position of the plane of the coil, by means of a spring which exerts a restoring torque to balance the deflecting torque due to current in the coil. The deflecting torque is $nAHi$ for small deflections, when a steady current i flows through a coil of n turns, each turn enclosing an area A the magnetic field, H being in the plane of the coil. When the steady condition has been reached for a direct current

$$nAHi = \tau\theta$$

where θ is the angular deflection of the coil and τ the torque per unit twist of the spring system. The system will also respond to applied alternating currents and it is under these conditions that it is used for recording mechanical effects. The moment of inertia, I, and the torsional stiffness τ decide the natural frequency of the system, $n[n = (1/2\pi)\sqrt{(\tau/I)}]$, and without damping, the response curve is flat up to about 0·2 of this natural frequency, then rises rapidly to resonance, falling beyond resonance. To extend the frequency range over which the response is flat, damping is introduced, and the mechanical considerations are identical to those of acceleration pick-ups, discussed in Section 2. For damping of 0·6 critical the frequency range is extended from zero to 0·8 of the undamped natural frequency. To make this range as wide as possible, the undamped natural frequency must be high, by making τ high and I low. Assuming that H is already a maximum, increasing τ and decreasing I by reducing the coil dimensions both result in a reduction of sensitivity. In general, the sensitivity is inversely proportional to the square of the natural frequency. A coil galvanometer developed by Films and Equipment to R.A.E. requirements is shown in Fig. 36a.

To increase the natural frequency by reduction of the inertia, the bifilar type of vibration galvanometer has been highly developed by the General Electric Company (U.S.A.) and Cambridge Instrument Company. Instead of a coil, a thin metal strip is used. The strip runs from one end round a spring tensioning pulley and back to the same end forming a loop. If a current is passed through the loop, which is in a strong transverse magnetic field, one side of the loop bows in one direction perpendicular to the magnetic field and the other in the opposite direction. A small mirror, fixed across the two sides of the loop, is thus rotated. In the absence of the mirror each half of the loop would be entirely independent, and would move a distance proportional to the current in it. Thus, if the mirror imposed no restraint between the wires, angular deflection for a given current would increase inversely with the distance between them. The restraint of the mirror increases as this distance decreases, so that in practice, there is an optimum spacing of about 2 mm for maximum sensitivity. Oil damping may be employed, the galvanometers being preferably in a thermostatically controlled heated compartment to avoid changes in characteristics due to external changes of temperatures.

8.2.2. *Magnetic systems*.—The aim in the magnetic circuit is to attain the maximum uniform flux in the air gap in which the coil or loop is situated. To keep the reluctance of this air gap to a minimum it must be as short as the coil or loop dimensions permit. The magnet used must have the maximum possible intensity of magnetisation and should be of one of the high-intensity alloys such as Alnico, Alcomax or Ticonal. Individual magnets for each galvanometer in a multi-channel equipment may be used. A common magnet block may also be used, the air gaps being either in series or parallel, either in conjunction with bifilar or coil types, and has the advantage that elements of differing natural frequencies and sensitivities may be rapidly interchanged without readjustment of the magnet system.

8.2.3. *Damping*.—The damping employed with coil galvanometers may be either fluid or electromagnetic. The latter has the advantages of almost complete independence of temperature, and is effected in the Miller version by winding the coil on an aluminium former and using a suitable shunting resistance. This is satisfactory for natural frequencies up to 200 or 300 c.p.s., but above this it is impossible to obtain sufficient damping, so that fluid damping, the coil being immersed in oil in a tube is used. The bifilar type necessitates fluid damping.

8.2.4. *Coil galvanometers with pointers.*—The coil galvanometers previously mentioned have their coils in a uniform unidirectional magnetic field and their deflection is recorded photographically by a light spot reflected by a mirror attached to the suspension. Another type employs a radial field, as in the ordinary moving-coil ammeter and voltmeter, together with a pointer attached to the coil which may be arranged to make a mark on a moving strip of paper. A typical example is that employed in the four channel pen recorder made by Messrs. Henry Hughes. The principle is shown in Fig. 36b. The common magnet system has the four gaps for the galvanometers in parallel, and the rectangular coil, wound on a metal former to give eddy current damping, has a soft iron armature at its centre, and is suspended by a phosphor-bronze strip, torsion in which provides the restoring torque. The undamped natural frequency is about 100 c.p.s. and the damping of about 0·7 critical, permits linear response up to about 70 c.p.s. The phosphor-bronze torsion strip carries a pivoted 'pen,' to the tip of which is applied a high voltage for recording on Teledeltos spark sensitive paper.

8.3. *Photographic Recording.*—8.3.1. *Two-dimensional cathode-ray tube trace.*—By far the greater proportion of oscillograph recording is at present effected photographically, both in the case of cathode-ray tubes and vibration galvanometers. Cathode-ray tube recording will be considered first, as unlike the vibration galvanometer, it is possible to apply independent signals, in two perpendicular directions, although this facility can only be made use of in stationary film techniques. It permits a record to be made relating two variables neither of which is time, for example a pressure-volume curve. The simplest method is to put the film or paper as close to the tube as possible, so that as the spot moves it affects the film or paper in its immediate vicinity. Owing to the thickness of the glass of the tube and the absence of focussing, the image is diffuse and unsatisfactory. This is overcome in the continuously evacuated cathode-ray tube, in which the plate is inside the tube, so that the electron beam impinges directly on it. This type of tube, however, is of complicated design and less convenient to use ; therefore, it is only used when extremely high writing speeds are required.

The disadvantages of the methods given above are overcome by using an ordinary still camera. It should have double or triple extension to permit focussing at short object distances, and the plate type, with focussing screen is convenient. Anything but a simple unspeeded shutter is unnecessary, as a single sweep of the spot may be used for rapid non-recurrent phenomena. A recurrent phenomenon may be synchronised to give a still trace on the screen, and photographed by a time exposure. This method is still the most satisfactory for high-speed transient recording, the relating of two variables neither of which is time, and in cases where a more complex moving film camera is either unnecessary or not available.

8.3.2. *Moving film camera.*—Where a phenomenon is to be recorded as a function of time, using either a cathode-ray tube or galvanometer, a moving film camera is used. The film is driven in a direction perpendicular to the direction of signal deflection on the cathode-ray tube or galvanometer. The film speed required is dependent on the maximum frequency to be resolved, and, if it is assumed that about 0·1-in. record length per cycle is the smallest tolerable separation, the speed in in./sec should be not less than one-tenth of the frequency (in c.p.s.) of the highest frequency required to be recorded. For work up to about 100 in./sec the continuous feed type of camera functions satisfactorily. Above this speed the mechanical difficulties encountered makes this type unreliable. The film is contained in a supply cassette and taken up at constant speed into a receiving cassette. The arrangement is, in general, similar to that of a normal ciné camera, except that the snatch mechanism to give an intermittent motion corresponding to successive frames is omitted. Owing to the increasing effective diameter of the take-up spool this must rotate at a gradually decreasing speed during the run if constant film speed is to be achieved, so that this cannot be driven through a rigid coupling. It is driven by a slipping clutch to keep the film tensioned, and the main drive is either by constant-speed sprocket with perforated material, or rubber friction roller with unperforated, through a gear system from a governed electric motor. The former rules out the possibility of slip in the system, but on the whole is more liable to 'jamming' due to split or inaccurate perforation. A well-designed system of either type is quite satisfactory however, but, as perforated material is available only in widths up to 70 mm, the friction system must be used for wide records. The length of film that passes through the system when it accelerates from rest to its maximum speed, and the length exposed between switching off the drive motor and the film stopping, are of importance. This tends to increase with increasing film speed and causes film wastage. This becomes serious at the higher speeds and is minimised by employing low inertia moving parts and high driving power.

If the required film speed is above the limit (about 100 in./sec) of satisfactory operation of the continuous feed camera, the drum type must be used. This consists of a drum around which a length of the recording material may be wrapped and held in place. The drum is rotated by an electrical or clockwork motor, through a gear box if a range of speeds is required. Paper speeds up to about 1,000 in./sec may be attained. The method is the only practical one for speeds of this order, and the disadvantages that the recording length is limited by the circumference, and the recording time by the paper speed, have to be tolerated.

8.3.3. *Writing speed*[75].—A relevant matter in photographic recording is the maximum writing speed (speed of the spot on the recording material) that may be recorded under given circumstances. This applies more particularly to recording using the cathode-ray tube, as the response of a vibration galvanometer limits the recording of high frequencies, and there is usually no difficulty in obtaining sufficient intensity by overrunning the recording lamp during the time of recording. The speed of the spot relative to the film is made up of two components, the signal velocity and the film speed. At frequencies where a consideration of maximum writing speed is important, however, the film speed component is much less than the maximum signal velocity and therefore may be neglected. Hence, the only relevant speed is that of the spot on the cathode-ray tube which is $2\pi af$ for a sine-wave of amplitude a and frequency f. Factors influencing writing speed are the sensitivity of the paper, the velocity of the spot and the brilliancy of the image of the spot. The brilliancy of the spot image is governed by the brightness of the spot on the cathode-ray tube's screen, the relative aperture (f number) of the lens, and the degree of optical magnification or reduction. The brightness of the spot on the screen is dependent on the beam current of the tube, the material and thickness of the screen, and the size of the spot on the screen under best conditions of electrical focus.

Information in the catalogues of Messrs. Mullard and Cossor show that, for a lens of aperture f1 and very great optical reduction, with 1,000 volts on the final anode of a blue-screened tube, the maximum writing speed expressed at the tube screen is about 20,000 in./sec. The maximum writing speed for any other condition is given by dividing this by the expression

$$N^2\left(1+\frac{1}{M}\right)^2 \times \frac{1{,}000^2}{V^2}$$

where M is the linear ratio of object size to image size, N is the f number of the lens and V is the anode voltage. (It is assumed that the fastest recording paper is used).

This shows that if $M = 2$, $N = 1{\cdot}9$ and the anode volts 1,000, the maximum writing speed should be about 2,500 in./sec. This has been found to be generally the case in practice.

The writing speed is proportional to the square of the final anode voltage, but, if this is increased, the deflection sensitivity of the tube is proportionately reduced, necessitating a higher undistorted output voltage from the signal amplifier. The use of a tube with a post-deflection accelerating electrode facilititates recording at high writing speeds without seriously reducing the deflection sensitivity of the tube. Tests have shown that the recordable writing speed is four times greater when a post deflector at 2,000 volts is used with a final anode voltage of 1,000 volts, than when no post deflector is used, with a reduction in sensitivity of only 25 per cent.

8.3.4. *Photographic materials*.—The relevant characteristics of photographic materials for this work are sensitivity, colour sensitivity and nature of the base on which the emulsion is coated. Recording paper is considerably cheaper than film, may be processed quickly and the black record on a white paper background is very convenient for analysis. On the other hand, film is more convenient than paper when a large number of copies is required, is less liable to shrinkage after processing and perforated paper is less robust than perforated film. Recording paper is normally blue sensitive only and can be used only with blue fluorescent screen tubes. Typical satisfactory recording papers are Kodak R.P.30 and Ilford B.P.1.

Among films, Kodak Fluorodak is satisfactory, or any of the panchromatic films. Kodaks make a special recording film Type 5B52 for use with blue-screen tubes which is designed for minimum image spread.

8.3.5. *Lenses.*—The primary requirement for a photographic lens for recording is high aperture (low f number). The tolerances on the corrections of a lens can be much less stringent than those of a lens for normal photographic use. As the light from a blue screen cathode-ray tube is confined to a very narrow band of the spectrum, it may be regarded as monochromatic, so that a recording lens does not require correction for chromatic aberration. Also, when the moving-film technique is used, the object is merely a line. These points, and the comparatively large permissible amount of spherical and other aberrations that can be tolerated have enabled special lenses to be developed purely for cathode-ray oscillography. An example is the Wray 2 in. focus f1 lens designed for an object-image ratio of 4 to 1 and covering 35 mm film. It should be noted that cylindrical lenses are unsuitable for recording the spot of a cathode-ray tube as they produce line images from a point object.

8.3.6. *Shutters.*—In the case of continuous film cameras there is usually no need for a shutter, as only a small portion of film in the gate becomes fogged, and this passes through before the camera reaches constant speed. Drum type cameras, especially for high film speeds, require a shutter arranged to open, preferably as the 'join' of the film passes the images of the spots, and to stay open for slightly less than one revolution. In multi-channel equipments an electromagnetically operated roller blind shutter, synchronised from contacts on the drum shaft has been used with success. An alternative arrangement to an automatic shutter is a simple manually operated shutter, which is opened immediately before recording, together with suppression of the tube spots, which are brought on for one drum revolution by means of contacts on the drum shaft.

8.4. *Optical Arrangement.*—8.4.1. *Cathode-ray tubes.*—For single channel work the arrangement of the lens and tube presents little or no difficulty, but the optimum arrangement of tubes and lenses in multi-channel recorders necessitates considerable consideration and ingenuity. The use of a separate lens for each tube, although permitting individual focussing, is often both unnecessarily extravagant and ruled out by the physical dimensions of large aperture lenses whose optical centres must be close together to meet the requirements that the images of all the spots must lie on a straight line perpendicular to the edge of the recording material. The use of surface-reflecting mirrors overcomes the mechanical difficulties introduced by the dimensions of the lenses, but loss of light occurs and they are not easy to keep clean. The problem is usually made easier by using one lens to photograph two or more tubes. In the Six Channel Cathode-ray Oscillograph Equipment (Mark I) described in Section 10, two lenses are used, each photographing three tubes, the axes of the lenses being inclined to bring the two sets of images into line. The angular covering power of the lenses is sufficient to permit this arrangement.

8.4.2.—*Vibration galvanometers.*—The basic requirements for photographic recorders incorporating vibration galvanometers are :—

(i) A light source. This is usually a tungsten line-filament lamp.

(ii) A mirror on the galvanometer suspension.

(iii) Means for focussing the reflected light to a spot on the film.

A mask is used in front of the lamp to pass light from a short length only of the filament, which serves as the object of the optical system. This must be focussed both along its length and across its width, so that a combination of cylindrical or spherical lenses, and plane, cylindrical or spherical galvanometer mirrors may be used. Spherical galvanometer mirrors provide the straightforward solution, but as they must be small and light are seldom used, owing to manufacturing difficulties. In the G.E.C. vibration galvanometers a plane mirror is used with a spherical lens immediately in front of it. A short focus cylindrical lens is placed immediately in front of the film (Fig. 37). This results in a very fine image.

The R.A.E. twelve channel oscillographs employ galvanometers with cylindrical mirrors, together with a cylindrical lens focussing in a direction perpendicular to that of the mirrors. To obtain greater deflection sensitivity, surface silvered plane mirrors are also employed (Fig. 38).

8.4.3. *Optical systems for time and phase marking.*—It is generally desirable that time marks be applied to the record. For relating an external event (*e.g.*, top dead centre of a crankshaft in engine measurements) to the record, it is necessary to apply other marks, each corresponding to such an event. This is done by making and breaking an external contact each time the event occurs, and using this to flash a lamp. These marks must be distinguishable from the time marks.

When either marks are being applied to the side or centre of the record, as a series of dashes along the length of the record, a pin hole may be illuminated by the light source and focussed on the film by a spherical lens. If narrow straight lines are required across the full width of the record, a cylindrical lens in conjunction with a line source such as the Cinema-Television Type T.N.1 gas discharge lamp may be used. An alternative method uses a light source behind a rotating slotted disc, driven by a synchronous motor, the interrupted beam being focussed by a cylindrical lens. If an interrupted transverse line is required a grid near the film is used (it is ineffective in any other position).

8.5. *Single Channel Recording Cameras.*—If the speed range is suitable for the work in hand an ordinary ciné camera may be easily adapted for continuous feed recording, by removing the 'snatch' mechanism and spacing the lens further from the film by means of a threaded collar. The Bell-Howell A-4 and Williamson G42B have been successfully modified in this way. Continuous feed cameras specially designed for cathode-ray oscillograph recording are produced commercially by many firms.

A simple drum camera may easily be constructed. Early investigations at R.A.E. were carried out with the aid of a simple light-tight box containing an aluminium drum accommodating 59 mm paper, and driven by a clockwork gramophone motor, with an f2.9 lens in a simple shutter accommodated at one end. For time marking a mercury vapour lamp illuminates a pin hole focussed on one edge of the drum. More elaborate models have since been made, providing synchronisation of the external event, and more automatic operation. Other drum-cameras have been manufacturered by Cossor Ltd. and the Southern Instrument Co. The Cossor model 3317 is driven by a clockwork motor, the speeds of the 35-mm film or paper (50cm lengths) being from 20 in./sec to 100 in./sec. The model 3369 is similar but employs an alternating current synchronous motor. Both cameras are equipped with 1 in. f1.9 lenses, and have contacts for synchronisation of beam suppression and external event.

8.6. *Timing Devices.*—When a variable is recorded on a time scale, as in the case of continuous feed or drum cameras and a measurement of frequency is required, it is necessary to establish this scale with as high a degree of accuracy as possible. This involves the application of time marks to the record at accurately known intervals. The method of applying the time marks necessitates a frequency source capable of producing an electrical signal at uniform and known intervals, and a lamp, pen or other method of applying marks corresponding to these pulses to the record.

8.6.1. *Frequency sources.*—The frequency source used depends on several factors :—

(i) The frequency required. This is in turn linked with the film speed. A higher frequency will be required for high film speeds if the time marks are not to be unduly far apart on the record, and to allow in the measurement for rapid fluctuations of speed.

(ii) The accuracy required.

(iii) The electric power available.

(iv) Space considerations. In ground work there is little need to limit the size of the source, but in flight, size is an important factor.

(v) The method of application of the time marks to the record.

(a) *Alternating current mains source.*—Under normal conditions the National Grid System operated by the Central Electricity Board gives an accurate 50 c.p.s. frequency. The long term average is extremely good, but short term accuracy is rather less. Abnormal wartime conditions have affected this accuracy considerably, and this, together with the very poor accuracy of local alternating current generating systems make the employment of this frequency for anything but fairly rough measurements undesirable. However, the method is very simple, and if one channel of a multi-channel equipment can be used, the mains frequency can be applied to the oscilloscope either directly or after suitable transformation.

(b) *Vibrating reeds.*—The normal power pack vibrator can be used either synchronised to the mains frequency (the disadvantages of this are similar to those in (a)), giving sharper pulses than the mains alone, or as a self-maintained device. The latter scheme is preferable. It has been found that an accuracy and constancy of $\pm$ 1 per cent even when the applied voltage is varied by $\pm$ 25 per cent from normal, can be attained. The system is compact and when greater accuracy is unnecessary, is often used. The frequency, which can be determined by comparison with an accurate standard, is about 100 c.p.s.

(c) *Clockwork mechanisms.*—For frequencies up to about 5 per second an ordinary clock mechanism, with a contact opened and closed by the escapement, is satisfactory. Owing to the loading imposed by the contact the accuracy is not quite as high as in normal clocks but, with a good design an error not greater than 0·1 per cent is possible.

(d) *Tuning forks.*—The high accuracy of a tuning fork is well known, 1 part in 10,000 is attainable with an elinvar fork without precaution such as thermostatic control, if the fork is valve maintained. Electrical contacts on the prong of the fork reduce the accuracy. The signal for operation of the marking device can be obtained from either the drive or pick-up coil of a valve maintained fork.

(e) *Oscillating valves.*—It is not difficult to design a valve oscillator having an accuracy of 1 part in 500, without recourse to crystal control over the range of temperatures encountered in flight. By careful selection of components with temperature coefficients of opposite signs, and the introduction of temperature compensating condensers, an accuracy and constancy of 1 in 20,000 over a temperature range of 50 deg C may be obtained from a Franklin oscillator. For greater accuracy crystal-controlled oscillators, if necessary with electronic frequency subdivision may be employed. The accuracy attainable is better than 1 part in 10,000 without thermostatic control of the crystal, and with this, accuracies higher than is necessary in the investigation of any mechanical effect may be attained. The frequencies for which a crystal is suitable are much higher than those required for this work, so that several stages of electronic frequency sub-division would be required.

(f) *Pendulums.*—A self-maintained gravity controlled pendulum may be made to give high accuracy, but on account of its size is not used for time marking purposes. However, a compact spring controlled pendulum, or rhythmatic relay, electro-magnetically maintained, may be used for low frequencies. It is arranged to operate a slave relay, which allows current to flow through a pea lamp twice per second.

8.6.2. *Methods of applying time marks to the record.*—The method used for applying the time marks to the record is decided primarily by the nature of the recording material. In general, this is photographic, so that a light source has to be operated by the frequency source. Suitable systems are :—

(i) *The use of a pea-lamp at low frequencies.*—This can be operated from a battery in series with either clockwork or electrically operated contacts. As the heating and cooling time of a filament lamp is of the order 1/50 sec, the method is suitable for use up to about 10 or 20 c.p.s. only. The duration of each light flash is such that the time marks appear as a series of dashes along the side of the record, except at very low film speeds.

(ii) *The use of a gas-discharge lamp.*—The same principle as (i) may be extended to higher frequencies by using a gas-discharge lamp. A compact light source is the hot-cathode mercury vapour type L/40. The blue light records satisfactorily on all light sensitive materials, the striking voltage is low (24 volts), and the deionisation time such that satisfactory operation up to about 100 c.p.s. is attained, but not sufficiently rapid to enable time marks to be put across the full width of the record at high film speeds. The record is similar to that obtained in (i). The use of a neon tube is not recommended, as the light is suitable only for use with panchromatic emulsions, and the striking voltage is about 90 volts.

A particularly suitable gas discharge lamp for the work under consideration is the Cinema-Television Type T.N.1 helium-nitrogen lamp. This is shown in Fig. 39. The electrodes are in bulbs at each end of a central capillary tube, in which an intense discharge takes place. The ionisation and deionisation times are a few microseconds only and this, coupled with the line nature of the light source, permits time marks to be applied as narrow straight lines across the full width of the record, even up to the highest film speeds, by using a narrow slit in front of the lamp and a cylindrical lens to produce a laterally divergent fine image. The lamp requires 1,500 volts to strike it, and the peak current is about 30 mA. Under continuous operation its life is short, so that it should be arranged that the lamp is operating only during the recording time. The lamp may be connected across the secondary of an auto-transformer to the primary of which a low voltage (either through the contacts of a vibrating reed or clockwork mechanism or from a squared, differentiated and amplified fork or oscillator signal) is applied.

(iii) *Synchronous motor with occulting disc.*—A signal from one of the pulse sources previously described may be used to drive a small synchronous motor carrying an opaque disc with a number of equally spaced, radial slots around its periphery. It is arranged that the focussed light falling on the film from a tungsten filament lamp is occulted by this disc except when one of the slits is between the lamp and film. The method may be used to apply narrow straight line time-marks across the whole width of the record, and has the advantage that the frequency of the time mark may be altered by using a disc with a different number of slots. Also the inertia of the disc and rotor evens out any slight irregularity in the intervals between successive time marks.

(iv) *Beam modulation.*—A simple method of applying time marks to a record from a cathode-ray tube is to apply a signal having a peak negative voltage of ten or more volts from one of the frequency sources described, to the control grid of the tube.

This produces a dotted trace, the intervals between the dots corresponding to the time marks. The objection to the method for anything but simple recurrent phenomena is that a transient may occur during the time for which the tube is blacked out, and not recorded.

8.6.3. *Typical time marking arrangement in multi-channel ground recorder.*—The arrangement adopted in the six-channel cathode-ray oscillograph recording equipment (Mark 1) is of interest. The range of film speeds is very wide :—0·5 to 1,000 in./sec. Assuming that 0·1 in. separation is the minimum desirable and 4 in. the maximum, this necessitates at least three time-marking frequencies. The initial frequency control is a 1,000 c.p.s. tuning fork. The timing frequencies selected were 5, 50 and 250 c.p.s. The latter is obtained by electronic division of the 1,000 cycles by two scale of two circuits. The 50 c.p.s. is obtained by division by a scale of five circuit, and the 5 from this by a scale of 5 and a scale of 2. The signal is obtained as a differentiated square wave in each case, and used to trigger a Cinema-Television Type T.N.1 gas-discharge lamp. A narrow slit is interposed between the lamp and a cylindrical lens, focussing a narrow line across the full width of the record.

9. *Single Channel Recording Equipments.*—9.1. *Introduction.*—In the previous two sections the special requirements of amplifying and recording circuits and recorders for use with electrical pick-ups were discussed without reference to specific equipments incorporating them. Present-day applications tend to demand multi-channel equipments, especially in the case of instruments for the measurement of vibration characteristics and strain, owing to the nature of the data required by the aircraft designer and aeronautical engineer. Multi-channel recording equipment is, of course, more complex than the single channel and, as it has a number of design problems peculiar to itself, typical examples will be discussed in some detail in Section 10. There are still many problems, however, whose solution demands single channel measurement only. It is appropriate, therefore, to describe some typical single channel instruments.

9.2. *General Purpose Recording Equipment for Resistance Wire Pick-ups.*—As stated previously, a large number of the measurements required are composed of static and very low-frequency variations. To ensure faithful reproduction of such signals, particularly when they are of a transient nature, it is desirable, though not always essential, to use directly coupled circuits in the amplifying and recording equipment. Therefore, an instrument has been designed which incorporates a bridge circuit, energised from a 50 volt large capacity battery, a directly coupled amplifier with a voltage gain of 20,000 and a frequency response constant from zero to 10,000 c.p.s. and a recording cathode-ray oscillograph directly coupled to the amplifier output circuit. The amplifier used is the Plessey–R.A.E. design described in Section 7. The equipment is designed for use in the laboratory and field, the various units fitting into a transportable console complete with cable compartment.

A convenient general purpose amplifier and oscillograph, found invaluable in this work, is the Mullard E800 oscilloscope which is available commercially. This amplifier is resistance-capacity coupled and has a voltage gain of about 8,000. Its response is constant to $\pm$ 5 per cent from 0·1 to 40,000 c.p.s. and its phase shift at low frequencies is very small, being about 7 deg at 1 c.p.s. and 25 deg at 0·2 c.p.s.

9.3. *General Purpose Recording Equipment for Capacity Pick-ups.*—A laboratory model of this type of equipment, which was built in three units of pre-circuit, amplifier and oscillograph, was marketed prior to 1939 by the Southern Instruments Co. and found a wide application in the early years of the war. It incorporated the tuned circuit pre-circuit and paraphase directly-coupled amplifier referred to in Section 4. The firm has since developed frequency modulated circuits which have been incorporated into single or multi-channel equipments.

9.4. *Wind-tunnel Pressure Recorder.*—This equipment, shown in Fig. 40, was designed for the measurement of irregular air pressure fluctuations, having frequency components from zero to 200 c.p.s. in the wind tunnel. The pressure to be measured acts on a pressure cell consisting of two thin steel diaphragms arranged as part of the iron circuit of two inductances. The two inductances form opposite arms of a bridge circuit, the other two arms being formed by an exactly similar pressure cell to which a fixed pressure is applied. The bridge is energised with alternating current of 3,000 c.p.s. and adjusted to be initially slightly out of balance. The modulated bridge output is amplified and applied to a cathode-ray oscillograph for observation, provision being also made for photographic recording on an external oscillograph when required. The amplified signal is also demodulated and the varying and steady components are recorded on two meters, giving the mean steady pressure and the root mean square value of the fluctuations. A frequency analyser is also provided, its chief function being to detect the presence of regular vibrations in the frequency range 5 to 200 c.p.s. in a background of irregular fluctuations.

The complete equipment consists of five portable units, the flux regulating transformer unit, oscillator and bridge supply amplifier, main amplifier, oscillograph and output meters and analyser. The oscillator comprises a temperature-compensated inductance-capacity circuit, with a frequency error for a temperature change of 30 deg C. of less than 0·1 per cent and a drift under normal laboratory conditions of less than 1 cycle per hour. This is followed by an amplifier having a push-pull output stage whose output is controlled by an automatic volume control system operating from a stabilised high-tension line and remains constant within 1 per cent over a reasonable period.

The main amplifier has a voltage gain of about 4,000 and a frequency characteristic determined by a two stage constant band pass filter having a pass band from 2,700 to 3,300 c.p.s. The response in the band 2,800 to 3,200 c.p.s. is constant within $\pm$ 1 per cent. The oscillograph is conventional using a VCR.139A cathode-ray tube and hard valve time base covering the range 1 to 1,500 sweeps per second.

The frequency analyser consists of an oscillator of similar circuit design to the bridge supply oscillator but with a variable frequency range of 3,010 to 3,210 c.p.s. The signal from the amplifier, picked up before the output stage, is fed into a mixer stage which also accepts the oscillator output. The combined tones are then rectified and fed into a selective amplifier which is a three-stage circuit degenerative at all frequencies except that of selection, the discriminating element being a Wein Bridge. The final indication appears on a $2\frac{1}{2}$ in. rectifier meter with its full-scale deflection related to that of the steady pressure and root-mean-square meters.

9.5. *Engine Indicators.*—A large variety of instruments exist for the measurement of aero-engine cylinder pressures against time or piston displacement and all the basic types of pick-ups have been used. The original Cossor indicator, employing a pressure sensitive composition resistor, has now been replaced by the Cossor-Dodds instrument which uses a capacity type water cooled pick-up[25]. Two channel equipment is available commercially comprising a Cossor split-beam cathode-ray tube and two independent amplifier and precircuit channels, a direct current polarisation circuit being used for the pick-up circuit. Roess[22] also described a condenser type indicator employing bridged-T balancing circuits discussed in Section 4. Another instrument employing a capacity pick-up and available commercially is the Philips indicator in which the pressure sensitive condenser and associated high frequency circuits form an integral unit which is fitted to the pressure chamber. In this system the modulated high frequency carrier is amplified and applied to the cathode-ray tube indicator without demodulation

Engine indicators employing magnetic pick-up units have been developed by the Admiralty[76,77] and the Anglo Iranian Oil Co. in conjunction with Standard Telephones and Cables[19], the latter being available commercially. In Germany, the method favoured for engine indicating is that employing quartz crystal pick-ups. A commercial instrument was marketed by Zeiss-Ikon which used a conventional pick-up design and associated circuits and was complete with a drum camera. This instrument suffers seriously from the well-known troubles of piezoelectric systems and no evidence of its use in Germany was seen. In its place the German aeronautical research establishments have developed an indicator with a quartz crystal water cooled pick-up of an improved design with special emphasis on a high natural frequency and freedom from harmonic resonances[50].

The method favoured at the R.A.E. for the measurement of aero-engine cylinder pressures is that employing capacity type water cooled pick-ups and the amplitude or frequency modulated carrier circuits discussed in Section 4. Emphasis has been laid on the measurement of engine cylinder pressure against an accurate crank angle base and equipment for this purpose has been designed and applied with satisfactory results. This equipment comprises two channels, one of which consists of the capacity precircuit, directly coupled amplifier, and cathode-ray oscillograph and the other of an amplifier and oscillograph for recording signals at 2 deg intervals derived from a magnetic pick-up in conjunction with a toothed wheel. The two cathode-ray tubes are so arranged that the pressure and degree-marker signals can be photographed simultaneously on the same photographic paper.

An important consideration in these techniques for the measurement of pressure is the effect of the connecting passages between the pressure chamber and the pick-up diaphragm. The problem resolves itself into a consideration of the pressure drop and resonance effects in the passages due to the acoustic impedance.

9.6. *Detonation Indicators.*—It does not appear to be established as to whether existing engine indicator pick-ups can respond faithfully to detonation pressures although this is claimed by the Germans[50]. Two instruments for detecting and indicating the intensity of detonation are, however, worthy of mention. The R.A.E.-Mullard indicator[51] is based on the measurement of pressure in the combustion chamber itself. The pick-up uses quartz crystals and its output is filtered until the high frequency pressure transient due to detonation is separated from the main pressure cycle. The detonation signal is applied to the grid of a gas discharge triode which may be either automatically or otherwise preset. A measure of the detonation intensity is given by the bias voltage required to prevent the gas discharge triode from triggering when the detonation signal is applied and the frequency of detonation is observed from a tuning indicator in the triode anode circuit which flashes for each discharge.

The Sperry-M.I.T. detonation indicating equipment is based on the measurement of the vibration of the cylinder which is influenced by the pressure vibration. The vibration is picked up with a magneto-striction seismic unit and a commutator device is fitted to eliminate vibration effects due to valve and piston motions by rendering the pick-up signals inoperative during irrelevant portions of the combustion cycle. The signal is amplified and used to trigger a neon lamp, an indication of detonation intensity being obtained by observing the minimum gain setting required to flash the lamp. A cathode-ray tube is also provided to indicate the signals from several cylinders simultaneously, and the switch gear is such that when detonation takes place in any particular cylinder or cylinders, the location of the latter can readily be determined. Both equipments have been used with some success in flight.

9.7. *Measurement of Power in Flight.*—A novel method for the simultaneous measurement of mean torque and rotational speed—the impulse or phase difference method—has been developed for the accurate measurement of power in flight. In this method the pick-up unit generates two trains of impulses, or two continuous alternating current signals, the number generated per second or the frequency of the alternating current signal being a measure of the engine speed and the time spacing of corresponding impulses or phase difference of the two alternating-current signals being a measure of the engine torque. An instrument on this principle, using an electromagnetic pick-up has been developed by R.A.E. in conjunction with Messrs. Rolls Royce[78]. The pick-up comprises two identical phonic wheels, consisting essentially of soft iron wheels with teeth cut around their periphery, and coils with cores of magnetic material. The wheels are attached to the shaft at the maximum possible separation and the corresponding coils are mounted on the engine casing. As the shaft rotates alternating currents are generated in the coils, the frequency being a measure of the shaft speed, and their phase difference a measure of the torque in the shaft. Each pick-up feeds into an amplifier stage, thence to a squaring and differentiating circuit, and the signals are then combined in a phase measuring circuit which indicates the mean torque on a meter. One of the signals is also passed to a scale-of-two counting circuit which indicates rotational speed on a second meter. This instrument has been used to measure torque in flight with an error of less than $\pm$ 2 per cent.

9.8. *Resonance Testing Equipment.*—This equipment records automatically the mode of vibration of an aircraft or component when subjected to a resonance test and overcomes the disadvantages of the straightforward method of recording, individually, the amplitudes of vibration at various points and comparing their phases with a standard signal. During the test[79] one pick-up unit is fixed at each station at which the vibration is to be measured, for example, along a wing whose flexural mode of vibration is required. The pick-ups are connected to alternate contacts on one bank of a selector switch, the intermediate contacts being earthed. A rotating wiper connects each pick-up in turn to the input of a suitable integrating amplifier which feeds the Y-plates of a cathode-ray oscillograph. Thus a vertical line proportional to the vibration amplitude is produced on the oscillograph each time the wiper is on a pick-up contact and a spot each time it is on an earthed contact.

By means of a second bank of the selector switch, the traces from each pick-up are spaced out horizontally across the screen by the application of suitable voltages to the X-plates. The positions of the traces across the screen depend on the horizontal deflecting voltage applied in conjunction with each signal, and these voltages may be chosen so that the traces are spaced in a manner corresponding to the spacing of the pick-ups along the wing. A Selsyn transmitter is coupled to the vibration exciter, which is of the rotary type, and this is connected electrically to a Selsyn receiver geared to the selector switch. Thus the selector switch is made to run exactly in step with the exciter and is arranged to connect each pick-up to the amplifier for the duration of two cycles.

A second Selsyn receiver is connected electrically to the transmitter on the exciter and this drives a contact maker which makes every two cycles of vibration. This contact is used to apply a voltage pulse to the grid of the cathode-ray tube which increases momentarily the brightness of the trace on the screen. By this means it is possible to determine the phase of the vibrations relative to each other, and, if necessary, their phase relative to the exciting force. A hand operated retard mechanism, calibrated in degrees, enables the operator to adjust the position of the bright spot on the ordinate. All that is usually required is to determine whether the various vibrations are in phase or in anti-phase. To do this the retard mechanism is adjusted until the phasing spots on the screen appear at the extremities (upper or lower according to phase) of the lines. When this condition is set, the brilliance of the trace may be reduced so that the lines are suppressed and only the spots at their upper or lower extremities are visible, together with a central base line of spots produced when the earth contacts of the selector switch are made. The resultant pattern on the screen thus gives the amplitude of vibration, correctly phased, for each pick-up, and thus gives a visual indication of the mode of vibration, the vertical scale being naturally exaggerated in relation to the horizontal one.

The equipment in its present form consists of three channels, each taking twelve stations, and arranged for simultaneous photographic recording. Normally the cathode-ray tube screens can be viewed through a mirror which has to be tilted to another position for recording. When the mirror is locked in this position, a single push-button initiates a series of automatic operations in which the film is exposed for the duration of one complete traverse of the selector switch and records a record number. Means are provided for winding the exposed film into a cassette and resetting the camera. A photograph of the equipment is reproduced in Fig. 41.

9.9. *Vibration Analysers.*—The importance of providing instruments for the satisfactory analysis of vibration, in place of the tedious method of computation by the envelope method or method of superposition, cannot be over-emphasised. In spite of this, it was found impossible to undertake serious work on the development of such instruments during the war, although some development, based on R.A.E. requirements, is now proceeding at Messrs. Standard Telephones and Cables.

In addition to the mechanical analysers, such as the Harvy Harmonic Analyser[80], many instruments have been devised to perform the necessary analysis by other than purely mechanical methods, and are capable of giving useful results in certain restricted ranges of application. A well-known electrical method is that based on the observation of Lissajou figures on a cathode-ray tube[81]. An ingenious optical method using variable area film records of the type produced in the R.A.E. Vibrograph and variable density sinusoidal records has also been devised[82].

Two basic types of electrical analysers have been developed by the General Radio Co. (U.S.A.), one using highly selective filter circuits—the heterodyne type (G.R. Type 736A)—and the other using degenerative circuits (G.R. Type 760A Sound Analyser)[83]. The degenerative type circuit results in a constant band width as expressed in percentage of the resonant frequency and therefore, has inherently the same type of selectivity curve at very low frequencies as at high frequencies. For the analysis of low frequencies such as occur in aircraft vibration it is, therefore, in general, superior to the heterodyne method and an instrument on this principle, companion to the type 761A Vibration Meter, is marketed by the General Radio Co., as the type 762A Vibration Analyser which deals with the frequency range 2·5 to 750 c.p.s.[84]. An interesting development in connection with vibration analysis is recorded in a series of three papers in the *Journal of the Society of Motion Picture Engineers*[70,71,72], in which equipment is described for recording the outputs of 13 amplifier channels on to 13 sound tracks in line on film in flight and delivering the reproduced sound track outputs at sufficient level to a suitable electrical analyser in the laboratory.

Another type of analyser worthy of mention is that designed by the Bell Telephone Laboratories and used successfully in flight by Pratt and Whitney[85] which, in conjunction with a vibration pick-up and a recorder, produces a curve of the amplitude of vibration at a given multiple or order of engine speed versus engine r.p.m. It covers 28 engine orders from $\frac{2}{5}$ to 10 times and, therefore, a frequency range of 3·33 to 500 c.p.s. for an engine speed range of 500 to 3,000 r.p.m. In principle, the complex signal from the pick-up is analysed and a particular component is rectified and moves the pen of the recording instrument in a vertical direction by an amount proportional to the amplitude of that component. The output of an electrical tachometer, which is coupled to the engine, is amplified and rectified and caused to control the motion of the recorder pen so that it takes up a specific position in the horizontal direction related to the engine speed. Therefore, each curve drawn on the chart denotes the amplitude of vibration for one particular order of frequency as the engine speed varies over the entire range.

In conclusion, reference should be made to a consideration given by Manley[86] to the application of electrical vibration analysers to the analysis of fluctuating stresses in aircraft propeller blades under operating conditions, in which the very high accuracy in frequency determination required in order to distinguish engine and propeller orders in certain cases and the effect of the unavoidable fluctuation in running speed of the engine are discussed.

10. *Multi-channel Recording Equipments.*—10.1. *General requirements.*—Although in some investigations successive single channel records from pick-ups at each of several positions meet the requirements, there are many occasions, *e.g.*, during vibration tests on an aircraft or the measurements of pressures in a multi-cylinder engine, when the phase relationships between phenomena occurring simultaneously at different parts of a structure must be determined. This necessitates the use of a multi-channel recorder, producing two or more accurately phased records on the same length of recording material, and therefore, on the same time scale. Even in cases in which phase relationships are of no importance, the use of this type of recorder facilitates rapid recording from a large number of pick-up stations.

Multi-channel recorders fall into two main classes. In the first, for use in tests in the laboratory or field, the primary design considerations are accuracy and ease of operation, and it is seldom essential to limit the size and weight. This permits the use of cathode-ray tubes having screen diameters of 3 or 4 in., and amplifiers obtaining their current supplies from well stabilised power packs. The second class is for use during tests in flight where lightness, compactness and

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automatic operation, are primary design considerations, and, although high accuracy is desirable, the final equipment has often to form a compromise between size and accuracy. Where its use is not essential the cathode-ray tube is not the most compact form of oscilloscope, and for frequencies up to about 1,000 c.p.s. the Duddell or D'Arsonval type vibration galvanometer leads to a more compact instrument. A recorder has also been developed for use both on the ground and in flight over a limited, but useful, frequency range, which utilises galvanometers, the movements of which are recorded by energised pens on spark sensitive paper.

10.2. *Problems Peculiar to Multi-channel Recording.*—The design and operation of multi-channel recording equipment requires the solution, not only of all the problems associated with single-channel equipment, but also of others peculiar to itself which may be classified as :—

(i) Effects due to close proximity of the channels working from common power supplies.

(ii) Effects resulting in time displacement of the traces.

(iii) Input circuits relating to the use of more measuring stations than available channels.

The first class includes interaction between the precircuits of various channels, between the amplifiers, and between the oscilloscope tubes or galvanometers. In the use of capacity pre-circuits of the resonant circuit type the most obvious method is to construct several circuits similar to that used for single channel work, each with its own 1 megacycle per second oscillator. This leads to difficulties, as the frequencies of the oscillators differ slightly, and beat notes are produced between them. This may be overcome by feeding the separator stages of all the pre-circuits from a single oscillator. In the case of resistance wire pick-ups using bridge circuits it is obviously advantageous to supply all the bridges from a common direct current source. This, however, imposes certain limitations on the possible bridge connections if serious interaction between channels is to be avoided. When the power source is common, not more than two variable arms may be used and these must be adjacent ones. Also, the earthed connection to the bridge must be made at the junction of the two fixed ratio arms. This means that neither end of any gauge can be earthed. Common ratio arms for all the bridges can be used. If it is found necessary to use more than two variable arms in the bridge, or if the two variable arms are not adjacent, a separate direct current source for each bridge must be used.

Interaction between the amplifiers may be minimised by careful screening. Effects due to coupling between amplifiers obtaining their power supplies from the same power pack are more serious. One method of minimising these is to keep the internal impedance of the power pack to a minimum, by using large decoupling condensers. The effect can be eliminated by using push-pull amplification in each stage of the amplifier. It is usually made negligible, if the output stages, which take a much higher anode current than the initial stages, are in push-pull. Interaction between the oscilloscopes is rarely encountered. The only case in which it is likely to be at all serious is when electromagnetic deflection is used for cathode-ray tubes.

It is particularly important in multi-channel recording, in which the major aim is to establish the phase relationships between phenomena occurring at different points, that errors due to phase shift should be minimised. Ideally the amplifiers and recording system should all have zero phase shift. This would produce a record corresponding exactly to the voltage produced by the pick-up, and there would be zero time delay in the system. At the frequencies encountered in mechanical phenomena, as well as the pick-up and galvanometer (if used) the phase characteristics of which are discussed elsewhere, the amplifier can also introduce an appreciable phase shift. If the angular phase shift produced by the amplifier is directly proportional to the applied frequency, the output voltage will be exactly similar to the input voltage, and will merely be delayed by the amplifier. This would not matter unless phasing marks with zero or negligible time delay were being used. In practice, with a resistance-capacity coupled amplifier, the phase angle is inversely proportional, not directly proportional, to the frequency. The only practical solution is, therefore, to make the phase angle negligible at the lowest frequency to be recorded. This can be achieved by the use of large intervalve coupling circuit time constants, by minimising the number of coupling circuits and by the use of negative feedback.

In addition to the time displacement produced by the amplifiers, a relative displacement of the records along the time axis may be the result of maladjustment of the recording images in their ' no signal ' positions. For no error the no signal positions of all the channels must lie on a line perpendicular to the direction of motion of the recording material and all signal movements must take place along this line.

A selector unit is required to permit the selection of the measuring stations in groups corresponding to the number of available channels. The grouping of specific stations must be possible, in particular the use of a common ' master ' station throughout the measurements. When bridge circuits are employed a preset balance control must be provided for each station.

A desirable feature of multi-channel equipments is the provision of a calibration signal automatically recorded during each measurement. This ensures accuracy and eases the operation, particularly as it is frequently necessary to employ channels of different sensitivity simultaneously.

10.3. *Multi-channel Recorders for Use in Flight.*—10.3.1. *U.S.A. equipments.*—(i) *The Sperry M.I.T. vibration recorder*[87].—This is a four channel equipment designed for vibration recording under airborne conditions. It is made up of five main parts—pick-up, selector switch, amplifiers, power supply and recording oscillograph with remote control. The equipment is intended for use with generator type vibration pick-ups, and the selector switch unit provides plug connections for twenty-four of these and for selection of them in groups of four for connection to the amplifiers. Internal terminal strips are provided together with two additional switch positions to enable any two predetermined groups of four pick-ups to be selected in these positions.

The amplifiers give constant current output per millivolt input over the frequency range 5 to 1,000 c.p.s. when used without integration. An integrating circuit may be switched in, and this, in conjunction with the vibration pick-up, which gives an output voltage proportional to the velocity of vibration, gives an overall response proportional to the amplitude of vibration. Two amplifiers are housed in one box.

The power supplies for all four amplifiers are obtained from a single power unit, operating from a twelve volt battery. The heaters of the amplifier valves, which are double triodes throughout, are supplied with twelve volts, which passes through the power unit merely for switching. The high-tension voltages are obtained from a small rotary converter which operates on 12 volts direct current input, and gives 300 volts direct current for the output valves. A stabilised voltage of 210 volts is also obtained for the anodes of the initial stages.

The recording oscillograph uses four Duddell type vibration galvanometers, together with means of photographing their spot deflections on a continuously moving 70 mm perforated film. The film is sprocket-driven at speeds of $12\frac{1}{2}$, 25 and 50 in./sec. Although laboratory checks have shown that these speeds were accurate and constant to $\pm$ 1 per cent, it was felt that means of applying time marks to the record were desirable. Accordingly a helium-nitrogen lamp and optical system have been fitted, so that narrow straight line traces can be applied across the full width of the record.

Provision is made for interposing a rotating mirror and lens system in the path of the beams reflected from the galvanometers, so that visual observation may be made on a ground glass screen. It is not possible to use this simultaneously with taking a record, and as there is only one mirror the time for which the spots are visible on the screen is small compared with the time of rotation. At high scanning speeds this results in an apparently less bright image.

When used with the Sperry-M.I.T. vibration pick-ups the overall magnification of the system is 150 times, *i.e.*, 1 in. on the record is equivalent to 1/150 in. displacement at the pick-up. As supplied, the equipment is intended for use only with generator type vibration pick-ups. It was necessary to extend its applications to include wire resistance strain units, and variable capacity gauges. In the former case a slight modification to the amplifier input circuit together with a reduction of negative feedback, is all that is required. Two types of pre circuit have been developed successfully. The first provides input connections for twenty-four working gauges, which may be selected in groups of four for connection to the amplifiers, and the second is similar except that pairs, each made up of one working and one compensating gauge, are selected.

For use with variable capacity gauges, units have been built up, each comprising an amplitude modulated capacity precircuit together with amplifier, and four of these units are connected directly to the recording oscillograph.

(ii) *The Miller multi-channel flight recording equipment.*—This equipment was designed especially for flight use in conjunction with vibration pick-ups, variable-inductance acceleration pick-ups or strain-gauges.

For vibration measurement electro-magnetic generator type pick-ups are employed, the outputs being applied to six similar condenser coupled amplifiers, whose outputs are connected to vibration galvanometers in the recording oscillograph. The amplifier gives constant response over the frequency range 2 to 5,000 c.p.s. and gives a maximum power output of 1/10 watt in a 6 ohm load. This output is produced by an input signal of approximately 2 millivolts when minimum attenuation is employed, an accurate attenuator giving steps of 3 db to a maximum of 60 db being provided. Six amplifiers are built as a single unit, each amplifier having on the panel a meter indicating the output and a neon discharge lamp arranged to indicate whether the amplifier is overloaded. An integrating circuit may be switched in and the response is then inversely proportional to frequency from 5 c.p.s. upwards. The power supplies for the six amplifiers can be obtained from either a 110 volt alternating current mains unit or a 12 volt rotary converter. The power consumption is about 100 watts. The dimensions of the six amplifiers are $9 \times 11\frac{1}{2} \times 12$ in.

For acceleration and strain measurement a carrier energised bridge technique is employed, variable-inductance pick-ups being used for the former and wire resistance strain gauges for the latter. The carrier frequency is 2,000 c.p.s. and a sense discriminating demodulating circuit is incorporated in the amplifier. The carrier frequency is removed by means of a two-stage filter and the demodulated signal passed via a direct coupled cathode follower matching stage to the galvanometer elements in the oscillograph. Six amplifiers are built as a single unit of about the same dimensions as that used for vibration measurements. The carrier oscillator and power pack form another unit, which can be supplied from either 110 volt alternating current or a 12 volt battery, the consumption being about 60 watts. This system is suitable for recording phenomena at frequencies from 0 to about 70 c.p.s., this limit being set by the filter networks and associated galvanometers.

The model D six channel recording oscillograph uses six moving-coil galvanometer elements and records on 4 in. photographic paper which can be loaded in daylight. The galvanometers have a common magnetic system, and elements having different undamped natural frequencies, ranging up to 2,000 c.p.s. can be fitted. The oscillograph can be controlled either locally or remotely and provision is made for automatically exposing paper lengths of two feet. Narrow straight line time traces at intervals of 0·01 second are applied by a slotted disc driven by a synchronous motor whose speed is determined by a vibrator. A 24-sided revolving mirror throws part of the light reflected from the galvanometer mirrors on to a ground glass screen, to permit visual observation, even during the time of recording. The time trace is also projected on to the screen, and the speed of rotation of the mirror is infinitely variable to permit synchronisation. Four paper speeds 2, 5, 15, and 35 in./sec, are provided, and provision is made for applying a record number and perforating or cutting the record. The oscillograph operates from a 12 volt supply, the current consumption being 7·5 amp, is very compact and weighs 42 lb.

The Model H recording oscillograph is basically similar to the Model D, except that twelve galvanometer elements, which may be interchanged with those of the Model D, may be accommodated, recording being on 6 in. wide paper. The time trace motor is controlled from a valve maintained 60 c.p.s. tuning fork.

The galvanometers for use with the Model D and Model H oscillograph have the following undamped natural frequencies :—40 c.p.s., 100 c.p.s., and 2,000 c.p.s.

(iii) *Equipment manufactured by Waugh Laboratories and Hathaway Instrument Co.*—A wide range of equipment for flight recording, using vibration galvanometers, is marketed by Waugh Laboratories. Equipment for both carrier and non-carrier techniques is available, and is in general very similar to that manufactured by the Miller and Consolidated Engineering Co. The type A.401.R portable oscilloscopes is of particular interest owing to its compactness and lightness. It incorporates six galvanometers with a common magnet system, recording being on two inch wide paper at one fixed speed, which may be either 3, 6 or 12 in./sec. It derives its power supplies from a special 8 volt battery fitted into a separate battery case. The dimensions of the recorder alone are $4\frac{1}{2} \times 12\frac{1}{4} \times 9\frac{1}{2}$ in., and its weight 22 lb, and of the battery case $2\frac{3}{4} \times 12\frac{3}{4} \times 9\frac{1}{2}$ in. and weight 17 lb.

The Hathaway Instrument Company also manufactures a range of recording instruments incorporating vibration galvanometers. In general, this is on similar lines to that of the Miller and Waugh Companies.

10.3.2. *Six channel electronic recording equipment for flight use.*—This equipment has been developed jointly by R.A.E. and Savage and Parsons Ltd. as standard equipment for flight recording at frequencies up to 1,000 c.p.s. It incorporates seven vibration galvanometers, one of which is used for applying a time-trace. The instrument is designed for use with either wire resistance strain gauges or generator type vibration pick-ups. The equipment is made up of the following units :—

(i) Recording oscillograph.

(ii) Time trace and calibrating voltage generating unit.

(iii) Six amplifiers made up of three units, each containing two amplifiers.

(iv) Precircuit for use with generator type vibration pick-up units.

(v) Precircuit for use with wire resistance strain gauges.

(i) *Recording oscillograph.*—This unit houses seven oil damped vibration galvanometers in one magnet assembly. The natural frequency of the galvanometers is such that their response is constant up to 1,000 c.p.s. The sensitivity is increased by multiple reflections from two surface silvered mirrors. After reflection the light beams fall on a cylindrical lens and are focussed on the recording film or paper which is driven by means of friction rollers at five speeds from 0·5 to 50 in./sec. The recording material is accommodated in light tight cassettes in lengths of 100 ft, and is 120 mm wide. Provision is made for applying a trace across the record corresponding to the make or break of an external circuit, for photographing the record number, for initiating an external event at the start of each record and for running the camera for preselected times of 0·5, 1 or 2 sec. For viewing, a fixed mirror may be interposed in the reflected beams from the galvanometers to enable the operator to see the amplitudes of the signals.

(ii) *Time trace and calibrating voltage generator.*—The time trace signal, applied to the centre galvanometer at preselected frequencies of 50 c.p.s. or 5 c.p.s., is obtained from a multi-vibrator synchronised to submultiples from a 200 c.p.s. valve maintained tuning fork. A sinusoidal calibrating signal of 500 c.p.s. is obtained from an oscillator whose frequency is controlled by the same tuning fork. The calibrating signal is applied automatically on the first three inches of the record. The unit also accommodates the equipment associated with the T.N.1. lamp.

(iii) *Amplifiers.*—The amplifier is resistance-capacity coupled, and has a constant frequency response from 1 to 1,000 c.p.s. when used without integration. An integrating circuit is provided giving an output inversely proportional to frequency (within $\pm$ 5 per cent) for a constant input voltage from 10 to 1,000 c.p.s. The circuit is shown in Fig. 31 and discussed in Section 7. Overall sensitivity is such that, without integration, an input voltage of 1 millivolt produces an output current of 4 milliamps in the galvanometer, and with integration, 1 millivolt produces 1 milliamp output at 50 c.p.s.

The amplifier comprises three conventional voltage amplification stages, followed by a phase splitter, and two cathode followers in push-pull. The galvanometer is directly coupled across the cathode loads so that no direct current flows through it. Although this results in a considerable wastage of output power the method ensures no phase shift in the coupling circuit. The total phase shift is less than 5 deg at 2 c.p.s.

(iv) *Precircuit for use with generator type vibration pick-ups*.—This unit provides means for selecting the pick-up units in groups of six from forty-eight, for connection to the six amplifiers.

(v) *Precircuit for use with wire resistance strain gauges*.—This unit provides input connections for forty-eight working gauges and forty-eight temperature compensating gauges (which may be replaced by internal resistors when temperature compensation is not required). Each working gauge is connected to a compensating gauge (or internal resistor) to form a potentiometer. Provision is made for the use of either 10,000 or 2,000 ohm gauges. Selection is as in the case of the vibration precircuit. In both cases the selector switch is motor driven and controlled by a telephone dial. An internal 50 volt dry battery is used for energising the gauges.

10.3.3. *Six channel carrier amplifier type* IT1-1 *for flight use*.—This equipment has been developed jointly by the R.A.E. and McMichael Radio to amplify the output from six resistance or inductance pick-ups. The pick-ups form part of a bridge circuit energised by 10 volts alternating current of frequency 2,000 c.p.s. The modulated bridge output is amplified, demodulated by a phase sensitive detector and passed to an output stage which feeds a galvanometer. Optional double integrating stages are available giving outputs proportional to velocity or displacement when acceleration pick-ups are used.

The equipment is in two units :—

(a) six amplifier channels,

(b) power supply and oscillator.

Each amplifier (Fig. 35) is preceded by two adjacent arms of a bridge circuit with a helical balancing potentiometer at their junction. The bridge is energised from a transformer whose secondary is centre tapped to earth. A function switch gives decreased gain and increased range of balance control for inductance pick-ups. It also allows a known out-of-balance (0·1 per cent) to be introduced into the resistance bridge. The output of the bridge is fed to a step-up transformer followed by an attenuator giving 20 steps of attenuation, each 3 db. The modulated carrier then goes to two stages of pentode amplification, resistance-capacity coupled with negative feedback from the anode of one to the cathode of the other, through a potentiometer to give a preset level of maximum gain. The output of the second pentode is choke-capacity coupled to a double diode phase sensitive demodulator fed with a reference voltage (225 volts) in phase with the bridge supply. The rectified output is smoothed in a resistance-capacity network and fed to a cathode follower output stage. (The galvanometer in series with a high resistance as the load, gives a virtually infinite impedance source). The bottom end of the load is taken to a stabilised negative voltage with a preset potentiometer to back off the standing current through the galvanometer.

Further positions of the function switch place a meter with bridge rectifier in series with the galvanometer, in such a way as to read the carrier before demodulation, carrier after demodulation, and the root-mean-square value of the signal voltage. Two integrating stages are made available by further positions of the function switch. The second stage is achieved by means of a pentode amplifier with negative feedback whose amplitude is proportional to the time differential of the signal. An overload indicator, in the form of a pentode amplifying the signal before integration, feeds a neon tube in its anode circuit which strikes at a predetermined signal level. This prevents the possibility of overloading the early amplifying stages with a signal that after integration may be small.

All direct current power for the six amplifiers is derived from the power pack, which operates off a 24 volt direct current supply or the alternating current mains. This power pack also supplies the carrier voltages required by the amplifier.

10.3.4. *Multi-channel galvanometer recorder, Type* 3-1.—This recorder, designed for flight or ground use by Films and Equipment to the R.A.E. specification, consists of a maximum of 12 separate galvanometer coils in one permanent magnet assembly, with an optical system enabling all 12 deflections to be recorded on 6 in. wide photographic paper driven at uniform speed in the range 0·5 to 50 in./sec. Therefore, it may be used, with the appropriate galvanometer coil and with or without suitable amplifiers, in the frequency range zero to about 2,000 c.p.s., further resolution being limited by the spot diameter. Increased record amplitude, without overlap, up to full paper width, may be obtained for less than 12 channels by omitting some of the galvanometer armatures. The recorder is operated from a 24 volt direct current supply.

A number of interchangeable galvanometer armatures are available, ranging from a natural frequency of 65 c.p.s. with a sensitivity of 0·01 mA/cm to a natural frequency of 3,000 c.p.s. with a sensitivity of 120 mA/cm. The 65 c.p.s. type may frequently be used with resistance and strain gauge pick-ups without amplification. A suitable armature for use with the carrier amplifier, described in Section 10.3.3, has a natural frequency of 130 c.p.s. and a sensitivity of 0·05 mA/cm.

The paper, contained in an external loading magazine, is moved at uniform speed by two rollers driven through a gear box by a governed 24 volt direct current motor. Speeds of 5, 10, 25 or 50 in./sec may be selected with an external lever. A further gear train may be easily introduced to reduce these speeds ten times. Means are provided for both cutting and perforating the paper after any length has been exposed, and for exposing automatically lengths of 2 ft.

Narrow straight lines, every tenth being thicker, are photographed across the full width of the paper during the exposure, at intervals of 0·01 sec. These are produced by a filament lamp, and occulting cylinder which is driven by a synchronous motor controlled by a 100 c.p.s. valve maintained tuning fork. When the lower range of speeds is used the drum may be made to give a time interval of 0·1 sec.

A counter advances by one unit each time the recording switch is operated and is photographed on the record. The galvanometer deflections may be viewed and measured on a ground glass screen under the loading door when the camera is unloaded, or on an external ground glass screen during recording. All the operating controls are duplicated in a remote control box.

10.4. *Multi-channel Equipments for Ground Use.*—10.4.1. *U.S.A. Equipments.*—(i) *Special oscillograph for Aberdeen Proving Ground*[88].—This instrument was developed by the Hathaway Instrument Company for recording strains, pressures and other phenomena in connection with gun tests. It is a six channel equipment incorporating six Brush crystal galvanometers and has a constant response over the frequency range 2 to 10,000 c.p.s. Direct current amplification is used, the maximum gain being such that 10/mV input signal produces full scale deflection of the galvanometers. The amplifier response is constant within 1 per cent from 0 to 5,000 c.p.s. and within 5 per cent from 5,000 to 9,000 c.p.s. (and is largely compensated by the galvanometer characteristic), and this has been obtained by negative feedback. Zero drift has been made negligible by the use of special cathode temperature compensation and regulated heater and plate current supplies. The input impedance of the amplifier is greater than 5 megohms. The amplifiers are mounted on standard relay racks, and recordings may be taken at sensitised material speeds up to 250 ft/sec.

(ii) *Multi-channel recording cathode-ray oscilloscope*[89].—This is a four channel recorder, using cathode-ray tubes, also developed for the Aberdeen Proving Ground for similar work to the equipment described above. The four tubes are grouped together on a single panel with their centres at the corners of a rhombus and are photographed by a single lens on a strip of moving photographic recording paper. The paper is 70 mm wide, and record lengths from 1 to 20 ft may be preselected. The paper is driven by friction rollers at speeds of 10 to 500 in./sec in eight steps, acceleration to full speed occurring within 25 milliseconds. The lens used is an f2·5 of 6·5 in. focal length. Time marks at 1,000, 100 and 10 per second are obtained by electronic sub-division from a 100,000 c.p.s. crystal controlled oscillator.

The amplifiers give a full useful screen deflection for 0·1 volt input when used at maximum sensitivity, and this frequency response is constant from 0 to 50 kc.p.s. and 3 per cent down at 100 kc.p.s. The phase characteristic is linear over the entire useful range. The maximum gain is approximately 10,000 and the zero drift is negligible over at least five minutes. Provision is made for either balanced or unbalanced input, and for an input impedance of either 10 to 20 megohms or 1,000 ohms. The output is push-pull and a panel mounted galvanometer is incorporated for balancing each stage.

Owing to the use of a single lens and the disposition of the four tubes the records do not appear to be on the same time scale, two traces being displaced with reference to the other two. It is considered that two lenses should be used to remedy this disadvantage.

(iii) *Four unit cathode-ray oscillograph*[90].—This is another equipment developed for use at the Aberdeen Proving Ground for measurement of blast pressure, strains, etc., during gun firing trials. Four cathode-ray tube channels are used—one for timing purposes, the other three for recording. Each oscillograph is built up as a separate unit which may be attached to the same camera at 60 deg intervals.

The tubes used have 9 in. diameter screens, and direct-coupled amplification is employed. Two preamplifying circuits are provided. One is condenser coupled, with an overall gain of 3,500 and constant frequency response from 5 to 1×10^6 c.p.s. The other is direct coupled, giving an overall gain of 5,300 with a constant frequency-response from 0 to slightly less than 1×10^6 c.p.s. The input impedance of any amplifier can be made 100 megohms by using an adaptor, the loss in gain being 30 per cent. A hard valve time base, is used, and there is provision for a time trace of 10,000 or 1,000 traces per second. Known calibrating voltage signals may be applied to the amplifiers from the 60 c.p.s. alternating current mains. The drum camera accommodates a film strip of length 60 in. and width 7 in., and gives speeds up to 3,600 in./sec.

10.4.2. R.A.E. *six channel cathode-ray oscillograph recording equipment* (*Mark I*).—This recorder has been developed to meet the needs both of the Ministry of Supply and British aircraft firms for a standard recorder for ground tests. For this reason the instrument is being made as universal as possible. The design is based on the experience gained on three and four channel equipments previously developed jointly by the R.A.E. and Cinema-Television Ltd. The complete recorder (Fig. 42) is made up of two G.P.O. 19 in. relay racks, and a main assembly. The latter houses the six 3½ in. cathode-ray tubes, type V.C.R. 529, together with the camera and six identical amplifiers. One rack contains the precircuits and the other a time pulse and calibrating voltage generator, and power packs other than the high-voltage pack.

The precircuits at present under constuction provide input connections for 48 generator type vibration pick-ups or 48 wire resistance strain gauges (or pairs of gauges if temperature compensation is employed). These may be selected in predetermined groups of six for connection to the amplifiers, by means of the first eight positions of a selector switch. Three additional positions are provided on this switch, and in these, groups comprising any six preselected pick-ups, may be selected. The strain gauges are switched into Wheatstone bridge circuits, energised by a built-in battery. Forty-eight variable resistors and micro-ammeter are provided so that these bridges may be balanced for each selector switch position before recording is commenced.

By operation of a rotary switch on each amplifier it may be made to have any of the following characteristics :—

(i) Constant response from zero frequency to 10,000 c.p.s. Maximum gain 10,000. Minimum gain 40.

(ii) Constant response from 5 c.p.s. to 10,000 c.p.s. falling sharply below 5 c.p.s. Gain as in (i).

(iii) Response inversely proportional to frequency from 5 c.p.s. to 10,000 c.p.s.

(iv) Response inversely proportional to frequency from 50 c.p.s. to 10,000 c.p.s.

Although when used as a direct coupled amplifier (position (i)) the circuit is very stable, any drift in the pick-up is amplified and applied to the cathode-ray tube. To overcome this disadvantage, position (ii) has been provided, and the circuit then has all the characteristics of a condenser coupled amplifier, so that pick-up drift is not amplified. Positions (iii) and (iv) incorporate integrating circuits so that, in conjunction with the velocity response of a generator type vibration pick-up, overall amplitude response is obtained. When there are no vibration frequencies below 50 c.p.s. position (iv) is used as it gives ten times more amplification at any frequency from 50 to 10,000 c.p.s. than position (iii), which is used only when lower frequencies are present.

The cathode-ray tubes are arranged with their axes slightly inclined to the vertical in two banks of three, each being photographed by one f1·9 lens of 3 in. focal length. The optical system is so arranged that the images of the spots of one bank of tubes fall in the spaces between the images of the spots of the other bank the six images lying on a line perpendicular to the edge of the recording paper.

The camera covers a very wide range of film speeds, from 0·5 to 1,000 in./sec. Although the continuous feed principle is more convenient than a drum camera it is not yet possible to obtain reliable operation of the former at speeds much greater than about 100 in./sec. The camera used in the recorder combines both principles, and paper speeds of 0·5, 5, 25, 50 and 100 in./sec may be obtained when continuous feed operation in lengths up to 100 ft is used, while as a drum type the speeds are 25, 50, 100, 250, 500, 1,000 in./sec. In the first case a record may be of any predetermined length up to the full hundred feet, while in the latter the record is always 30 in. long.

A 1,000 c.p.s. tuning fork is used to control the frequency of a 500 c.p.s. calibrating voltage of predetermined amplitude which is applied automatically to the first 3 in. of each record. It also controls the frequency of time pulses at intervals of either 2, 4, 20, 40 or 200 milliseconds. The equipment provides synchronisation for an electrically-controlled external event and means for recording a dotted straight line trace across the record, corresponding to the make or break of an external contact.

10.5. *Four Channel Pen Recorder.*—This recorder may be used for low-frequency recording both on the ground and in flight. Its main advantage is that records are ready for examination immediately, as 'Teledeltos' recording paper, which blackens when a direct current voltage is applied to it by means of a pen, is used. The standard recorder made by Henry Hughes Ltd. has four pen galvanometers, whose working frequency range is 0 to 70 c.p.s. and sensitivity 200/mA for full scale deflection. These record on 3 in. wide recording paper, accommodated within the recorder in lengths of 100 metres. Stationary pens on each side and in the centre of the paper record time traces as a series of dots at intervals of 25 milliseconds. The timing pulses are obtained from a 40 c.p.s. phase shift oscillator accurate to within 0·1 per cent, which triggers a Strobotac in series with the primary of a transformer. The paper is driven by a 24 volt motor at speeds of 5 and 15 cm/sec. To the recorder is connected a unit containing the four 3-stage symmetric amplifiers, and their associated power supplies. The amplifiers are condenser coupled except that transformers are used for coupling to the 8 ohm galvanometers.

High-tension supplies for the amplifiers are obtained from rotary transformers. The overall frequency range over which the response is constant is 5 c.p.s. (set by the amplifier) to 70 c.p.s. (set by the galvanometers).

The standard equipment is useful for many applications, but is limited in the lower frequency range, and has the disadvantage of having no precircuits. Joint development by R.A.E. and Messrs. Henry Hughes Ltd. has resulted in equipment in which both disadvantages are overcome. Four precircuits, comprising 2,000 c.p.s. alternating current energised bridge circuits, the variable arms of which may be either wire resistance strain units or capacity pick-ups, together with carrier amplifiers and phase discriminating demodulators, and direct coupled push-pull cathode follower outputs are all built up as a single unit. The impedance of the galvanometers has been increased to enable the cathode followers, of which they form the load, to be operated more efficiently.

11. *Applications.*—11.1. *Introduction.*—The instruments and techniques described in the foregoing sections have been applied to the solution of a variety of different problems associated with aircraft development, design and performance and the measurement of a variety of different quantities related to the aircraft and its components has been undertaken. Although the applications of these techniques are more or less limitless, a sub-division into the following fairly well-defined classes is appropriate :—

(i) Investigations of aircraft vibration excited by the power plant or aerodynamic disturbances, as in the case of flutter.

(ii) Behaviour of land and seaplane structures and landing gear on take-off and landing.

(iii) Performance of aircraft power plant and services, *e.g.*, the aircraft hydraulic system.

(iv) Installation and performance of aircraft armament.

(v) Performance of aircraft instruments under excessive vibration.

(vi) Design and performance of aircraft emergency devices, *e.g.*, seat-ejection devices.

(vii) Investigations on techniques and processes associated with aircraft construction, *e.g.*, welding machines.

A few typical examples of these applications and the results obtained will be discussed in this concluding section in order to illustrate the particular technique involved, the type of work which may be undertaken by such a method, and the form and nature of the results obtained. Brief reference only will be made to each example, and typical records only will be reproduced. Fuller discussions on similar and allied problems will be found in the references.

11.2. *Vibration Characteristics of Hurricane in Flight.*—This was the first attempt made at a comprehensive measurement of engine and airframe vibration using four channel electronic vibration recording equipment. The data were required to supplement the results of ground resonance tests and provide a basis for the design of flexible engine mounting. Since the vibration amplitudes, frequencies and their relative phases in three mutually perpendicular directions at a large number of points were required, it was essential that multi-channel equipment be used in place of the more conventional instruments, such as the R.A.E. Vibrograph.

Measurements were taken at an altitude of 10,000 ft under steady flying conditions. Photographs showing the installation of some of the recording equipment and pick-ups are reproduced in Figs. 43, 44, 45 and typical records in Fig. 46. The tests were successful except for the phasing measurements at frequencies below about 30 c.p.s. where the pick-ups were unsatisfactory due to the effect of temperature on their fluid damping. A few mechanical failures of pick-up units on the engine were also experienced due to the presence of excessive vibration.

11.3. *Testing of Shock Absorbers of Aircraft Landing Gear.*—The dynamic performance of the combination of tyre and shock absorber of an aircraft controls the reactions applied to the airframe structure during landing so that it is important to verify that these reactions do not exceed those for which the structure is stressed. For this reason designers try to save structure weight by fitting more efficient shock absorbers which supply smaller reactions. Drop testing of a new design of undercarriage is undertaken in order to provide a basis for the assumptions made in the prediction of the energy absorption performance of its shock absorber[91].

When an undercarriage, suitably loaded, is tested by the free fall method, using electronic recording equipment, the measurements required are :—

(i) The deceleration of the loaded undercarriage assembly.
(ii) The overall vertical movement of the falling mass.
(iii) The strut closures.

These quantities are photographed simultaneously in a transverse direction on a moving film or paper. (i) is measured by means of a capacity type accelerometer ; (ii) and (iii) by means of wire wound linear potentiometers with their moving contacts attached to appropriate points on the falling mass. The equipment used for this work, the three channel drop test recorder, has been mentioned in Section 10 and its associated pick-ups in Sections 4 and 5.

Fig. 47 shows a typical unit set-up for test in a vertical slide drop testing machine with the acceleration pick-up unit and movement rheostats in position. Figs. 48, 49, 50 are reproductions of typical records showing various combinations of retardation, movements, pressures and strain at various points of units under test. The record reproduced in Fig. 51 illustrates some of the information which it is possible to deduce from such measurements. For instance :—

(a) The drop test machine release mechanism operates satisfactorily.
(b) The transient response to the $-1g$ line is poor. This implies that either the mechanical structure does not allow the trolley to fall freely, or that the high frequency response of the amplifier is limited, possibly due to the introduction of high frequency filtering to overcome the resonance of the acceleration pick-up.
(c) The trolley does not run freely in the guides ; during the drop it suffers momentary decelerations. Sticking of the trolley immediately following impact could cause considerable error in the peak deceleration of the record.
(d) Resonance of the accelerometer is shown at release, tyre impact and commencement of closure and return of the oleo strut. The natural frequency of vibration of the accelerometer is about 250 c.p.s.

The record also shows excessive 50 c.p.s. mains ripple (equivalent to about $0{\cdot}1g$).

In addition to measuring the retardation and closures in an undercarriage it is sometimes necessary to measure the strains in particular members. Fig. 52 shows the position at which strain was measured in a *Halifax* tail wheel during drop testing and Fig. 53 gives some typical records.

11.4. *Tests on Live Line Pump.*—Pressure measurements were taken on a Live Line pump in an appropriate hydraulic circuit to test the effect of modifications introduced to reduce the pressure transients occurring on reaction. The pump was tested at three speeds, four capacities being used for each speed, the pressure transients being recorded in each case with a capacity type pick-up unit and associated equipment described in Sections 4 and 9 respectively. Typical results are reproduced in Fig. 54.

11.5. *Pressure Fluctuations of a Lockheed Hydraulic Pump Mk. IV, Series I.*—Data on pressures were required to determine whether some pump failures encountered could be due to surges of pressure. Measurements were taken on a ground rig similar to a typical aircraft hydraulic system and selector valve gear enabled the condition prevailing when the undercarriage is raised and lowered to be simulated. Capacity type electronic equipment similar to that previously described was used and a typical record is reproduced in Fig. 55.

The record confirmed many of the points already known about this hydraulic system, such as the pressure peak caused by the first wheel locking in the ' up ' position. It also showed that there is no sudden rise at any point of the operations. Even the abnormal operating conditions which cause the by-pass valve to chatter shocks the system less than the drop in pressure for normal operation of the selector valve. The sudden release from 2,000 p.s.i. fails to resonate the hydraulic circuit. The records show conclusively the satisfactory operation of the pump and there is no evidence of pressure surges of sufficient magnitude to cause damage to the pump.

11.6. *Measurement of Loads on Front Mounting of Hispano 20 mm Cannon.*—Intensive investigations of this nature have been made in order to determine the performance of various guns and obtain design data for their mountings. This particular example is included to illustrate an interesting method of measurement in which the pick-up unit, of the variable capacity type, is an integral part of the experimental gun mounting on a ground rig. The gun mounting, incorporating the pick-up unit, is shown in Fig. 56 and typical records are reproduced in Fig. 57.

11.7. *Investigations on the Effects of Gun Reactions on Aircraft Structures.*—The aim of this work was to provide design guidance for the mounting of guns in aeroplane structures in the form of information on the loads occurring in the mountings and supporting structure during firing. This should include information on the distribution and impulsive nature of these loads. The investigation included measurements with both 20 mm and 40 mm guns.

As an example, the measurements on a *Hurricane* installed with four 20 mm cannons are taken. Strain measurements were made at the stations shown in Fig. 58 using wire resistance strain units and the recording equipment already described. Typical records, chosen from a total of 180 taken for single shots and bursts from the outer cannons and all four cannons together are reproduced in Fig. 59. The detailed results are fully reported elsewhere, but to illustrate the type of information obtained Fig. 60, showing the distribution of the peak stresses at run-out, is reproduced.

Measurements have also been taken on guns mounted in turrets and the *Lancaster* mid-turret fitted with two 20 mm Hispano cannon is taken as an example. Strains produced when the two guns were fired aft were measured and also the fore-and-aft vibrations of the turret in the plane of the guns and on the floor of the turret. Figs. 61 and 62 show typical records and Fig. 63 shows the location of the measuring stations and the computed maximum stresses at each station.

11.8. *Investigations on the Effects of Gun Blast on Aircraft Structures.*—The aim of this work was to provide practical guidance for designers on how best to ensure that fuselage and wing structures in the region of guns withstand blast effects, the main variables considered being the gun position relative to the structure, plate thickness and riveting, stringer and frame stiffness and elastic and inertia properties and stringer and frame spacing. The measurements taken with electronic equipment included the measurements, with wire resistance strain gauges, of the impulsive stresses occurring in the structure and the blast pressures arising near the panels.

Investigations were made on a series of experimental panels, forming one face of a stiff rectangular box, and on various aircraft. The effect of blast from the two 20 mm short-barrel Hispano cannon firing aft together from the mid-turret of a *Lancaster* aircraft is taken as typical of this particular type of investigation. Typical records are reproduced in Fig. 64. Fig. 65 shows the positions of the measuring stations on the fuselage relative to the muzzle of a cannon and the maximum stresses, computed from the strain records, are encircled on the diagram.

11.9. *Determination of the Size of Restriction Required for Use with Hydraulic Pressure Gauges.*—It was suspected that failures of hydraulic pressure gauges in flight were due to fatigue caused by their response to the fluctuating pressures in the hydraulic systems. It is well known that a restriction in the gauge pipe line reduces the intensities of the fluctuations before they reach the gauge, but information was required regarding suitable size of restriction.

The natural frequency of vibration and the damping characteristics of a typical gauge were obtained by means of electronic measuring equipment comprising photoelectric cell, amplifier and cathode-ray oscillograph. From a second gauge a pressure time record was obtained with a fixed leak in the pipe line. This enabled a mathematical solution to be obtained to the problem. Fig. 66 shows the results of a test on a typical gauge fitted with a constriction. The graph confirms that the gauge and constriction act in a similar manner to a leaky electrical condenser. Thus, both systems have the same response to transients and to recurring fluctuations and the response of the gauge to sine waves is similar to that of an electrical low pass filter as shown in Fig. 67.

From the measured values of the natural frequency and damping characteristics of a typical gauge, together with the justifiable assumption that the gauge can be represented dynamically as a simple elastic system, the response of the gauge needle is given by the curve of Fig. 67, the measured damping coefficient Δ being 0·18 and natural frequency 25 c.p.s. If the two response curves are combined the response of the gauge at resonance can be reduced to approximately 2 per cent that of the unrestricted gauge. In this particular case it is seen that a restriction of about 0·25 second time constant would guard the gauge against damage from transients due to starting conditions and from recurring fluctuations caused primarily by cyclic irregularity of the pump delivery and the torsional fluctuations in the pump drive.

11.10 *Acceleration Measurement in Connection with Seat Ejection Development.*—Methods of seat ejection are being developed to overcome the serious difficulty experienced by crews of modern high-speed aircraft in making successful emergency escape by parachute when the speed of the aircraft exceeds about 400 m.p.h. The device under development consists essentially of a ram, attached to the seat, and fitting into a cylinder containing a cordite charge. This charge is detonated either electrically or by percussion and the explosion ejects the seat to which the pilot is harnessed, at an angle of 15 deg to 20 deg to the vertical. In order to ensure clearance of the fin of the aircraft, the ejection velocity in most cases must not be less than 60 ft/sec, and, as the acceleration stroke can rarely exceed 3 ft in present designs, it is necessary that the pilot withstand accelerations of at least 20*g*. This is approaching the physiological limit for a human being ; thus, one of the major problems in seat ejection is to ensure that the acceleration takes place in the best possible manner and that all peaks are eliminated. During development therefore it was necessary to take accurate measurements of the build-up of accelerations during ejection.

Typical records, taken on a ground rig and in a *Meteor* in flight, are reproduced in Fig. 68.

11.11. *Characteristics of Light Alloy Spot Welding Machines*[92].—Information was required on the variation with time of electrode tip force, transformer current and voltage, and their phase relationship during a welding cycle, in connection with the development of satisfactory light alloy spot welding machines and techniques. Two methods were used for electrode tip force measurement, one using resistance wire strain gauges and the other a capacity pick-up unit. A toroidal air core coil surrounding the electrode was used in conjunction with an integrating circuit for the current measurement. Simultaneous recording of all three variables was made with the three channel drop test equipment previously described.

Three typical records are reproduced in Fig. 69. The operation of the pneumatic cycle for the machine on which measurements were taken is shown in Fig. 70. Application of air pressure to the top of a cylindrically housed piston forces the upper electrode down to make contact with the sheets to be welded. This condition when contact is made is represented by points P on Fig. 69. From P to Q the electrode tip force increases as the downward pressure on the piston increases, the pressure on the underside of the piston remaining approximately constant. The change in slope of the records at R is caused when the spring A, Fig. 70, comes into operation, and the cylinder housing the piston starts to rise. When the pressure has built up to a predetermined value the air is exhausted from the underside of the cylinder. The resulting increase in electrode tip force is known as the ' forge ' and the point Q on records 1 and 2 corresponds to the commencement of this operation. (Number three is the record of a weld made without the use of this forging force). A sharp increase in force, point T on the records, is caused when the cylinder comes up against a mechanical stop on the machine. At point V the forging force has reached its maximum. The final operation, the start of which is shown on the records, is the application of pressure to the underside of the piston to raise the upper electrode from the completed weld. Points R′ and T′ correspond to points R and T respectively.

The current and voltage records appear in anti-phase due to the toroid connections adopted. A reversal of the two toroid connecting leads would result in the records appearing in phase.

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F

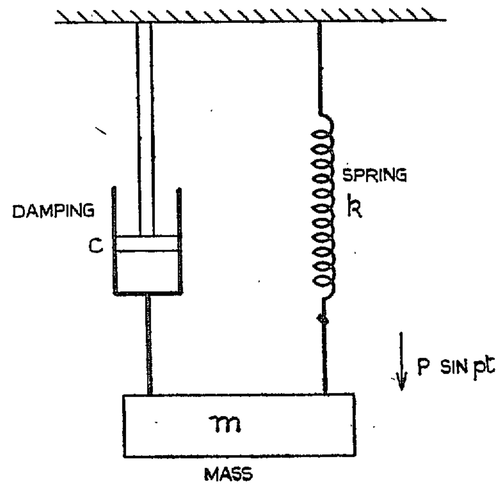


FIG. 1. Mechanical system of acceleration pick-up.

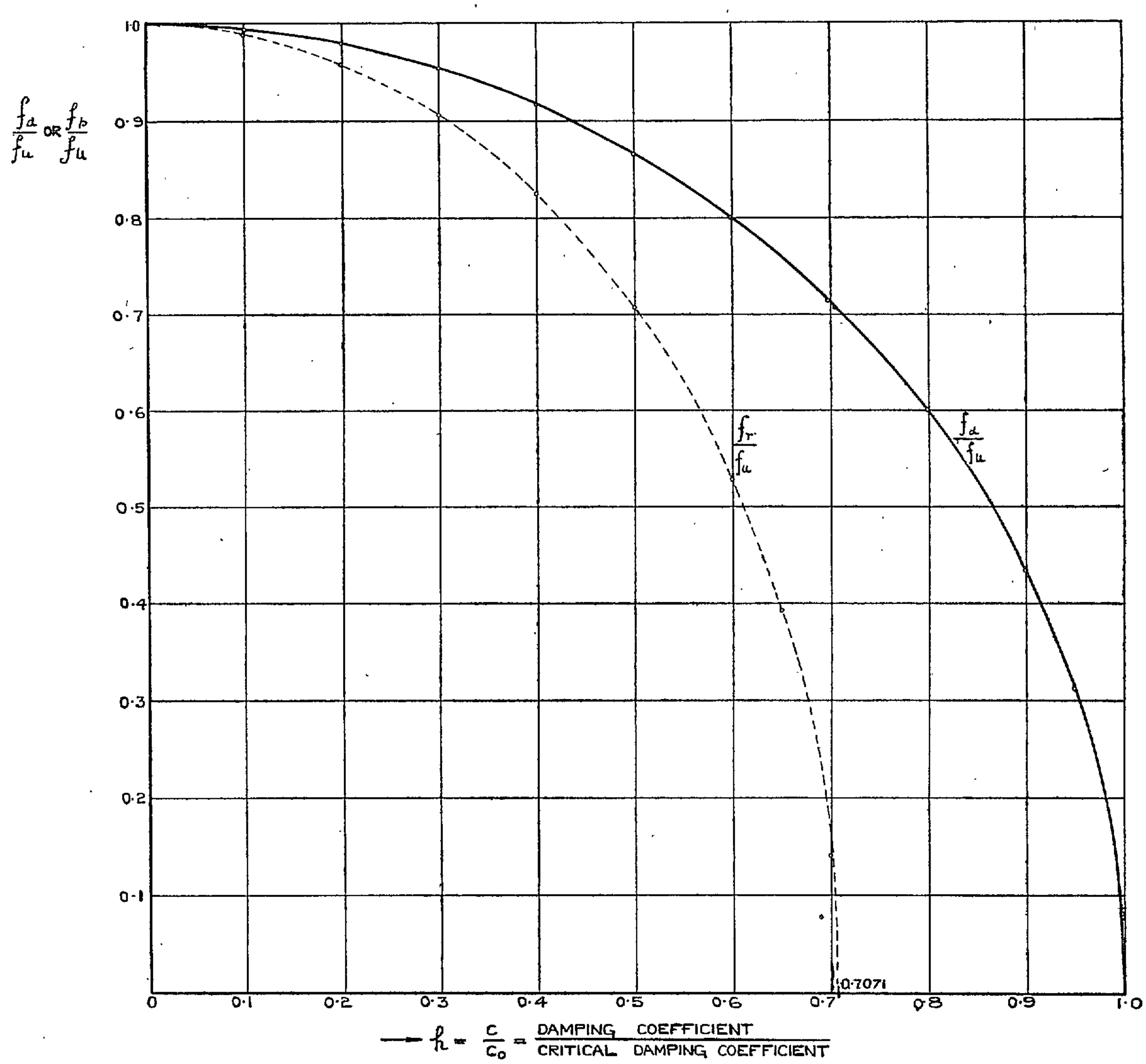


FIG. 2. Variation of damped natural frequency with damping for accelerometers, galvanometers and vibration pick-ups, and variation of resonant frequency with damping, for accelerometers and galvanometers.

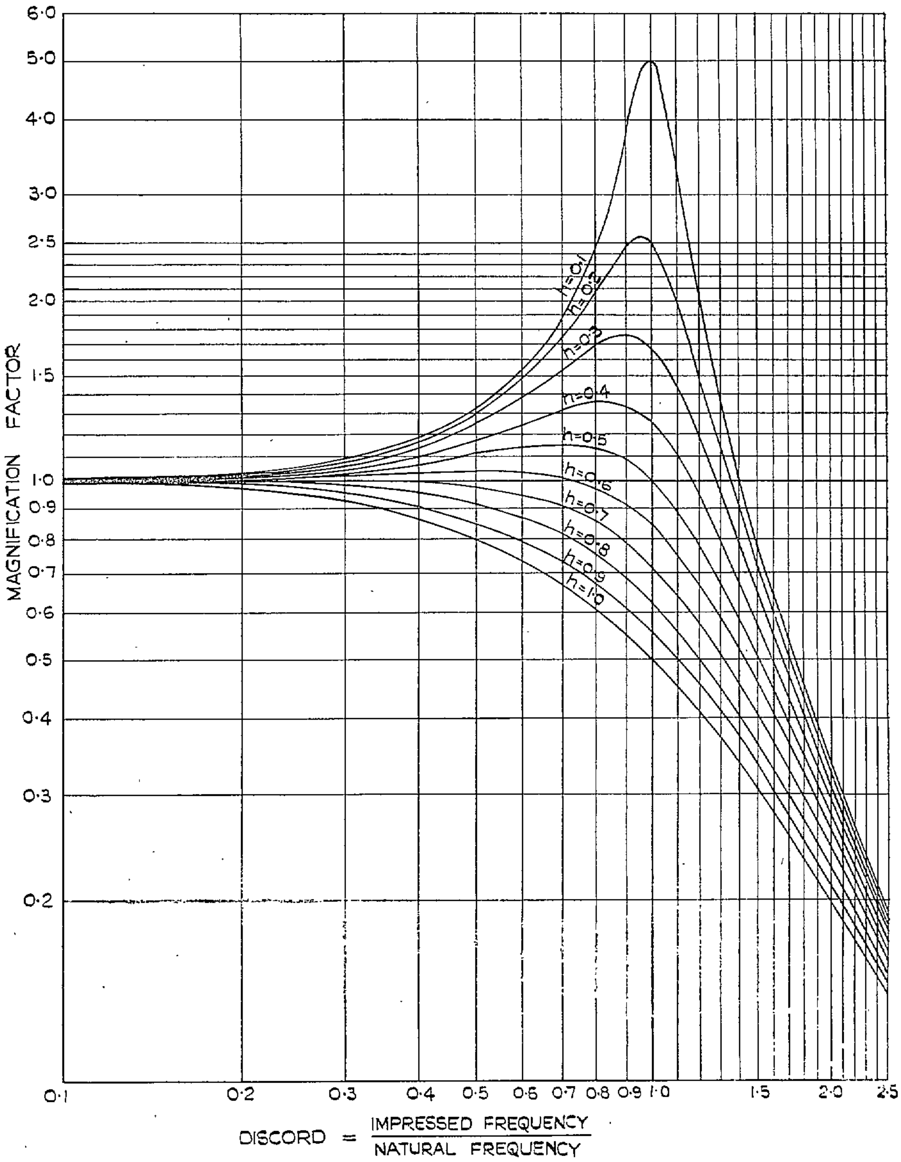


FIG. 3. Response of accelerometer system to impressed acceleration of constant amplitude.

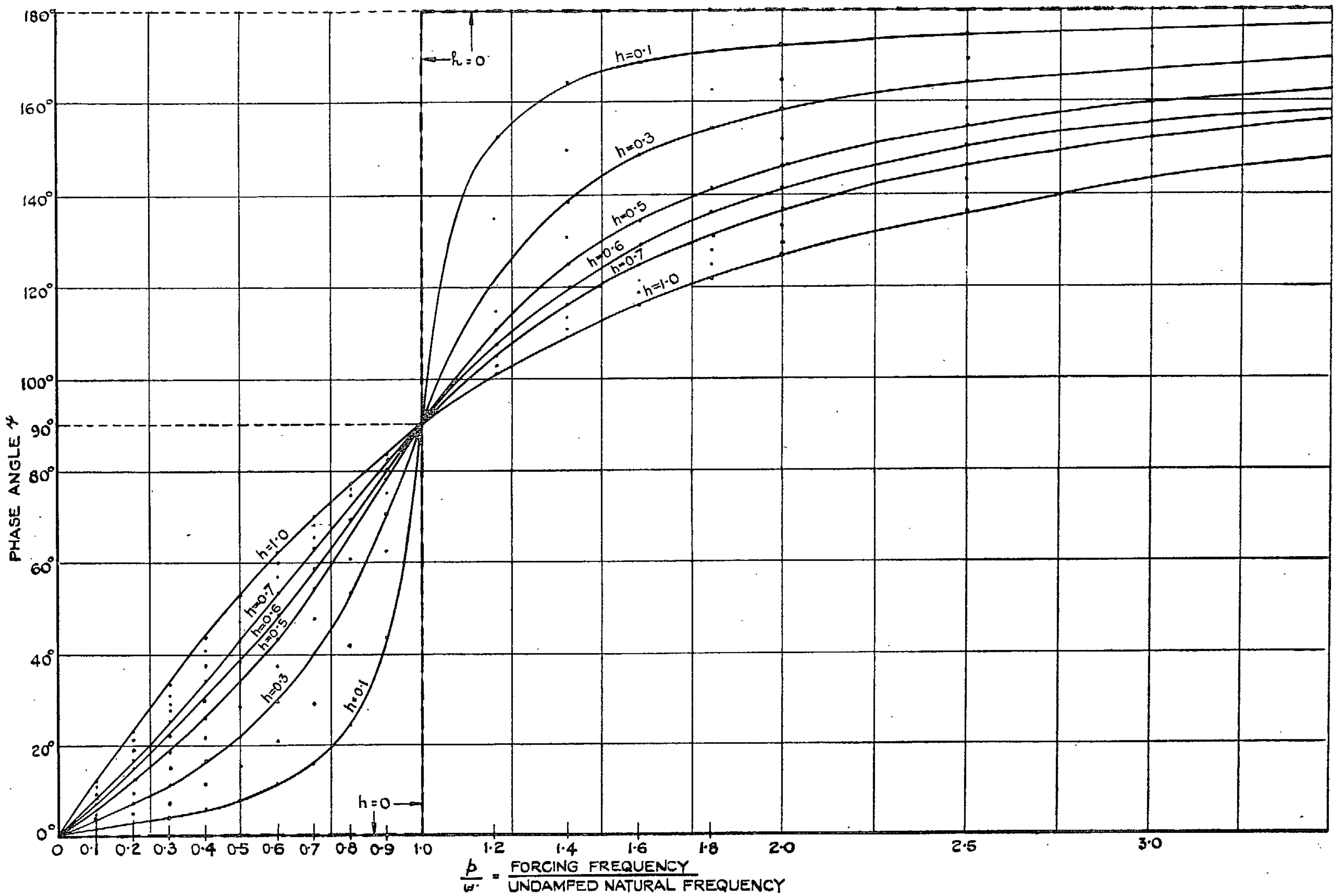


FIG. 4. Variation of phase angle with damping for a mechanical system.

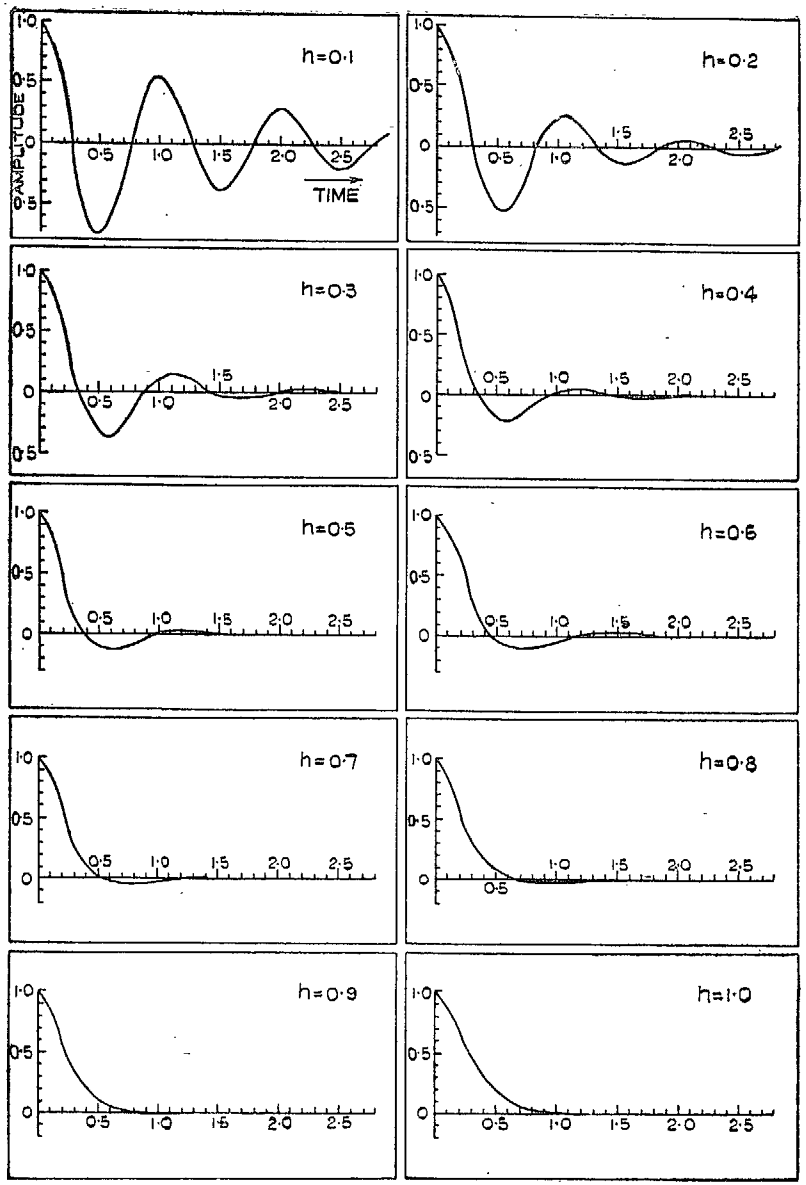


FIG. 5. Decay curves for different damping factors.

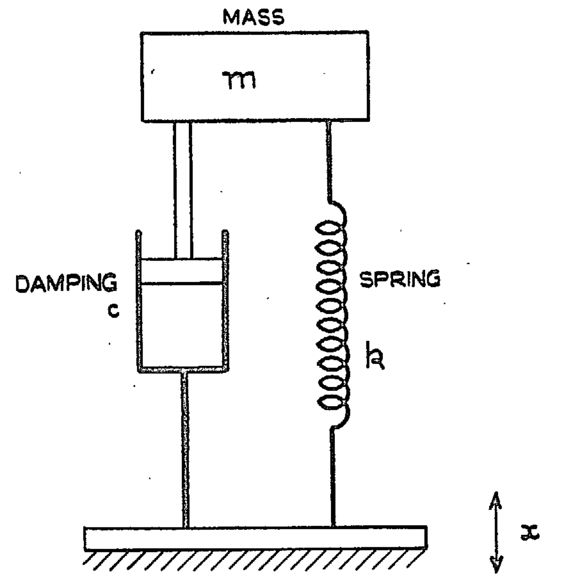


FIG. 6. Mechanical system for seismic vibration pick-up.

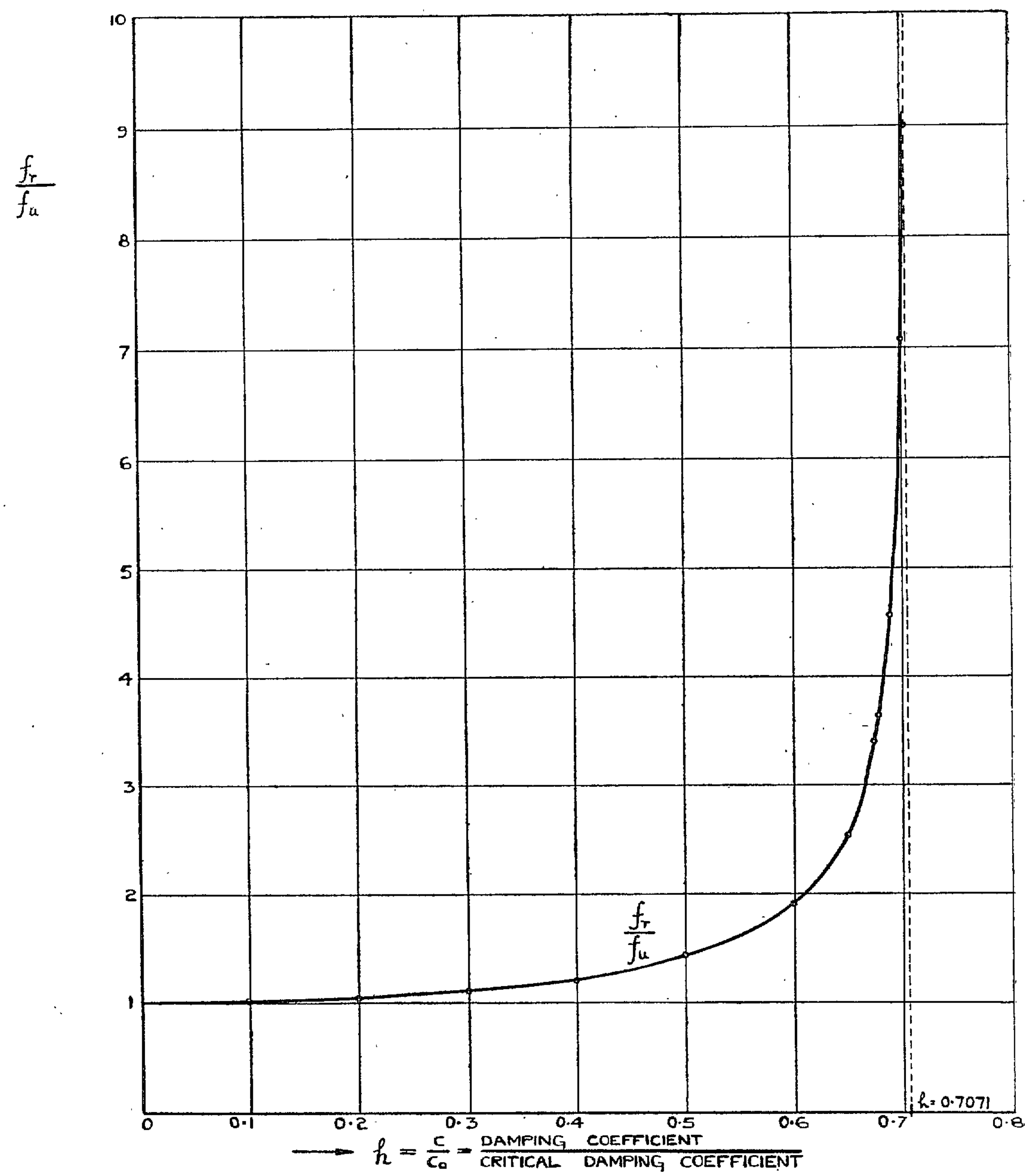


FIG. 7. Variation of the resonant frequency of seismic type vibration pick-ups with damping.

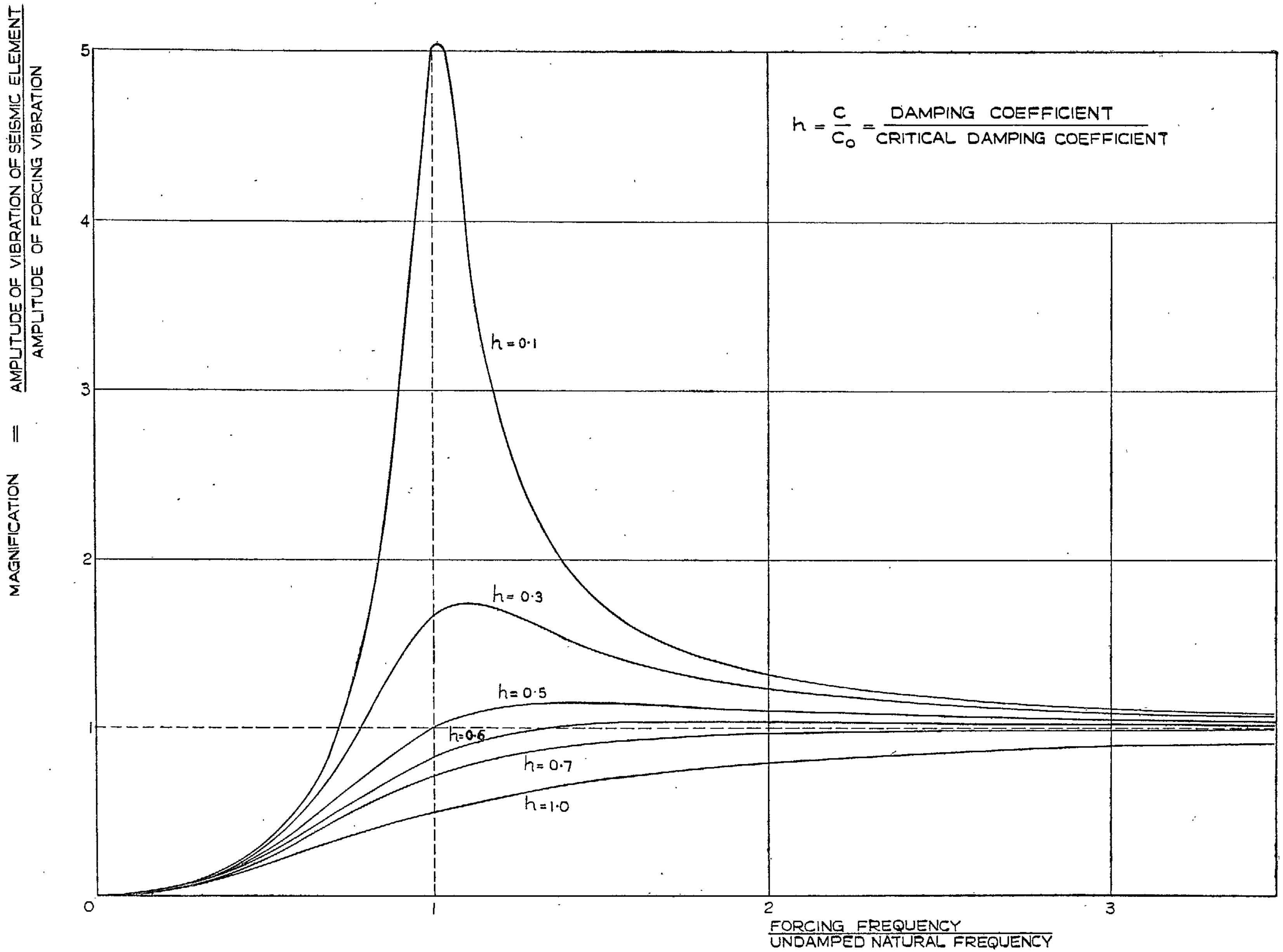


FIG. 8. Seismic pick-up variation of amplitude response with frequency for different degrees of damping.

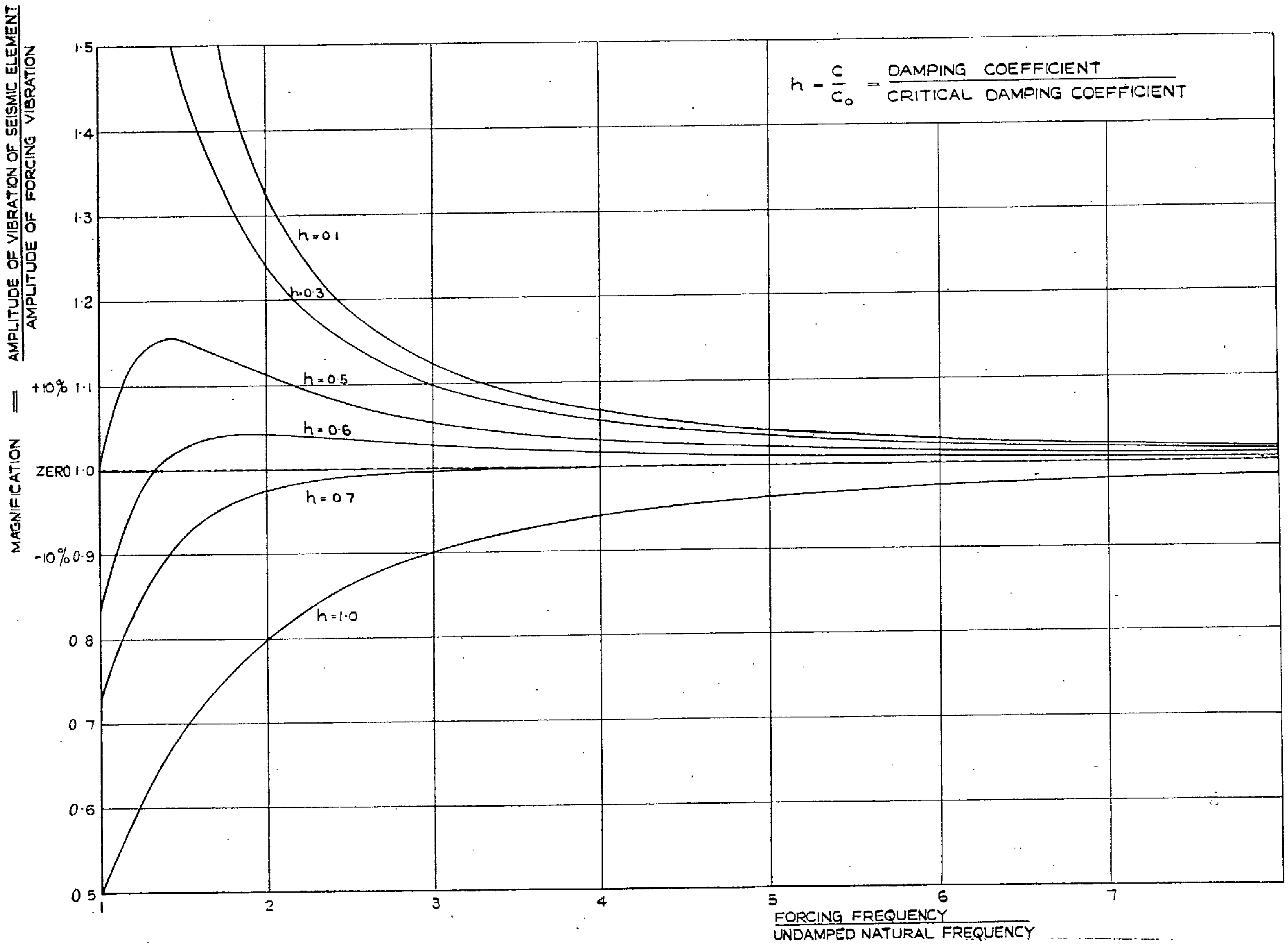


FIG. 9. Seismic pick-up variation of amplitude response with frequency for different degrees of damping.

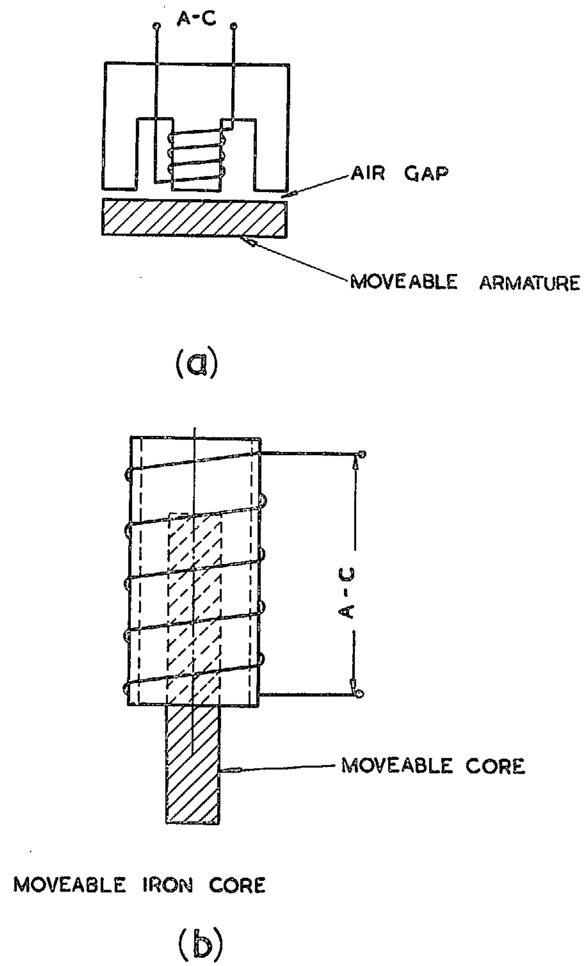
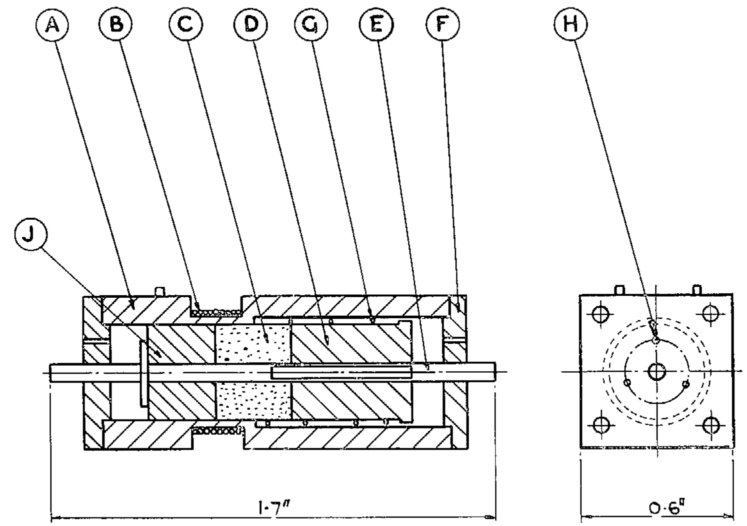


FIG. 10. Principle of variable inductance pick-ups.



A EBONITE FORMER
B COIL, 10 TURNS OF N° 28 S.W.G. COPPER WIRE
C FERROCART CORE
D BRONZE CORE
E SPINDLE, HARDENED STEEL
F BEARING, PHOSPHOR BRONZE
G SPRING, 4 TURNS N° 26 S.W.G. STEEL WIRE
H AIR DAMPING HOLES
J EBONITE PACKING PIECE

FIG. 11. Variable reluctance pick-up.

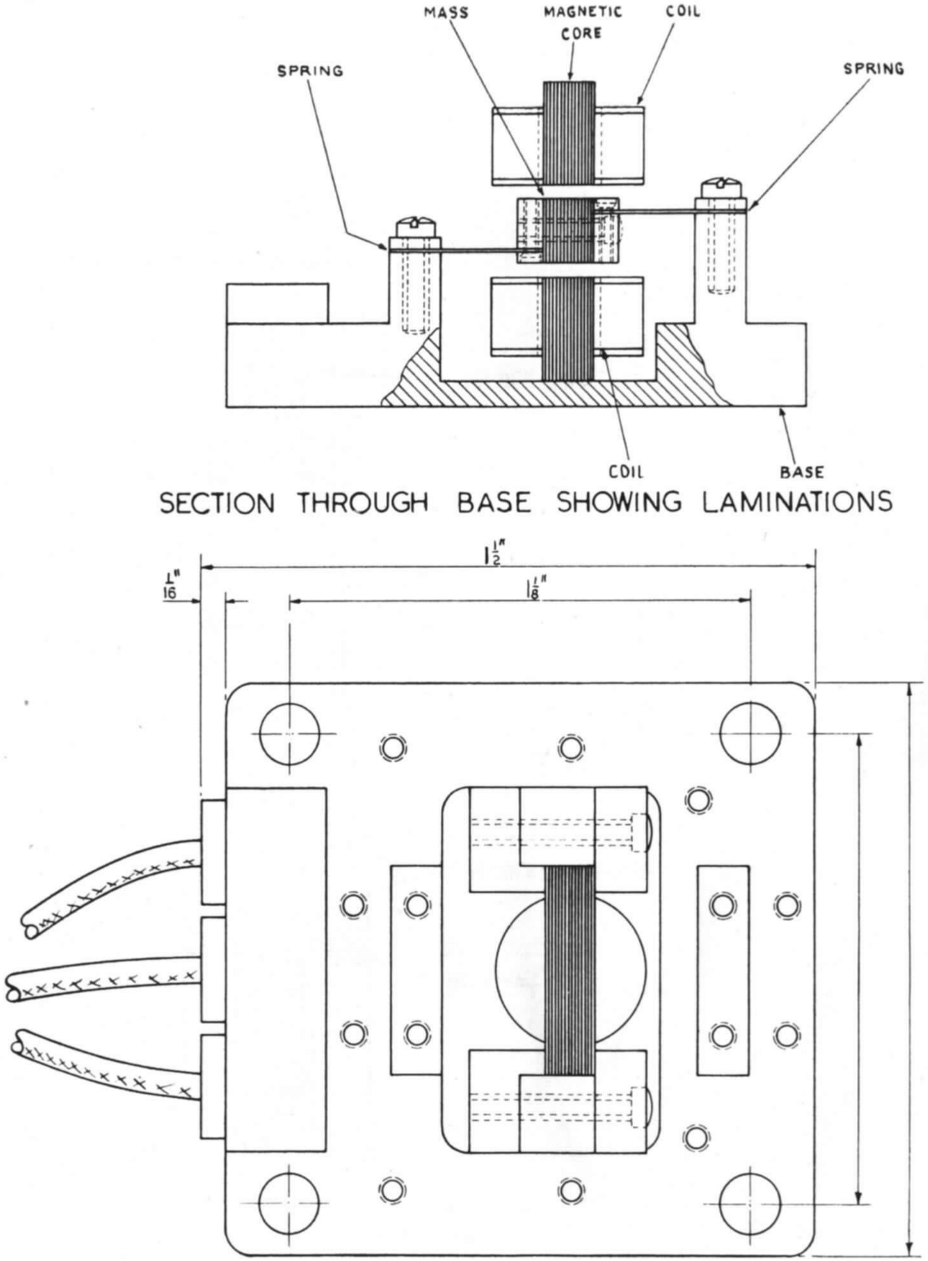


FIG. 12. Acceleration pick-up—Inductance type.

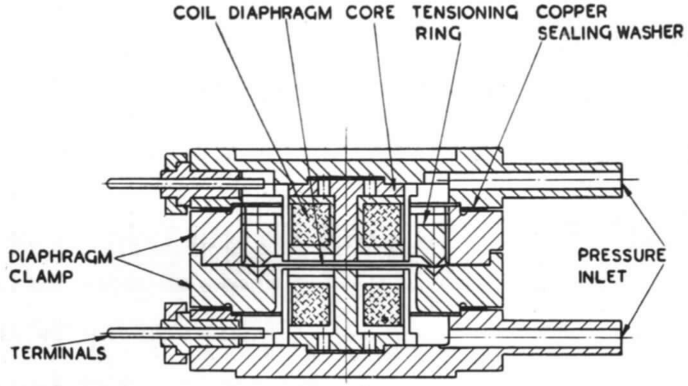


FIG. 13. Pressure pick-up—Inductance type (± 10 p.s.i.).

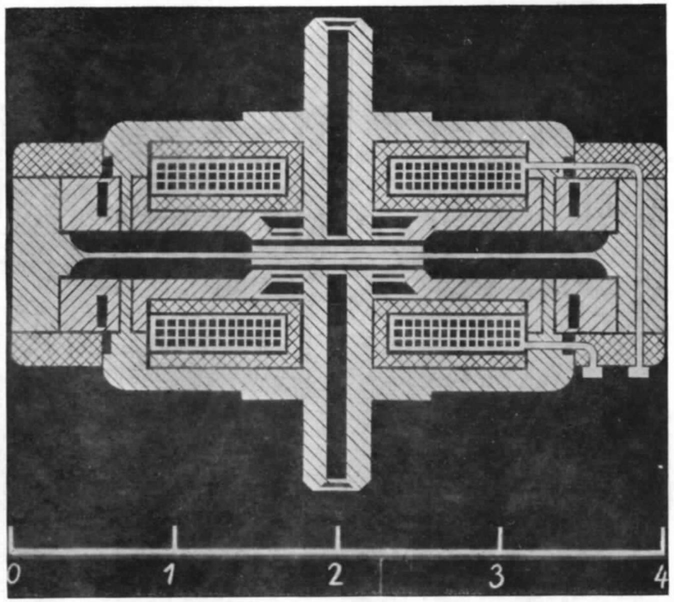


FIG. 14. Inductance type pressure unit.
(German)

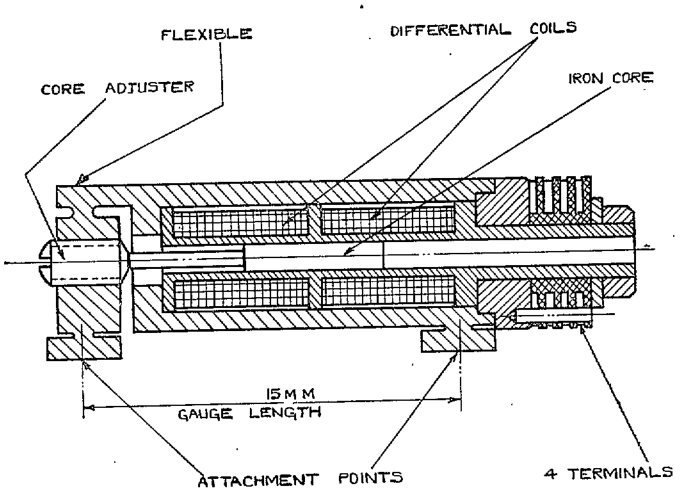


FIG. 15a. Moving core type inductance strain unit.

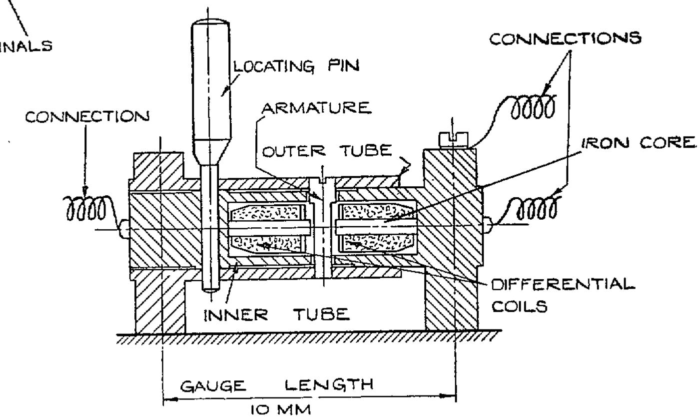


FIG. 15b. Variable air gap type inductance strain unit.

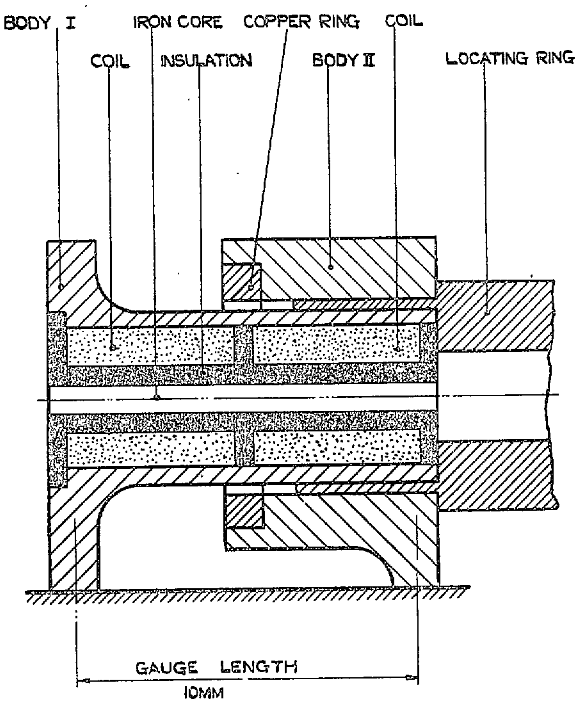


FIG. 15c. Eddy current type inductance strain unit.

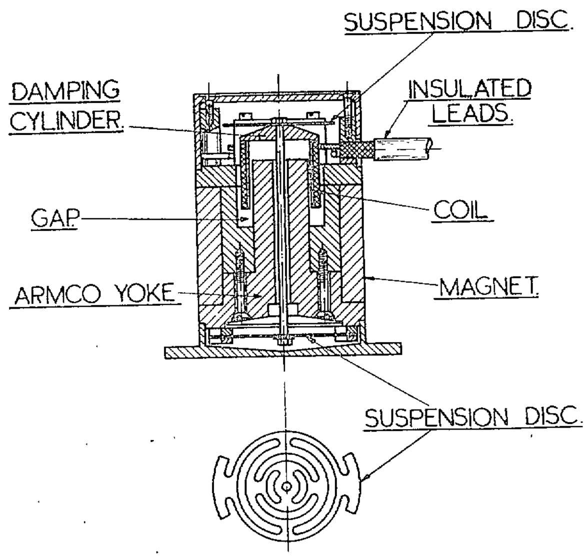


FIG. 16. Generator type pick-up unit.
(R.A.E.–Cambridge instruments)

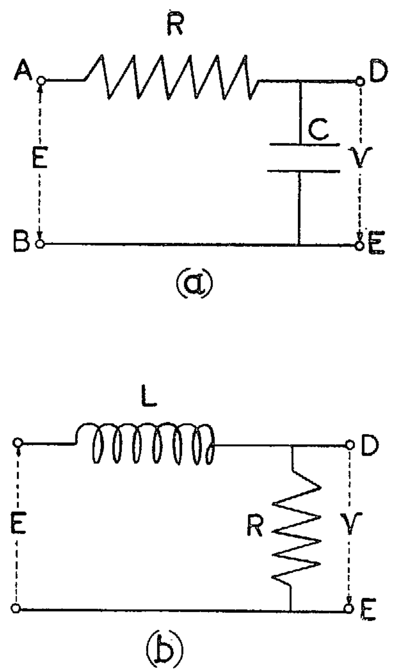


Fig. 17. Integrating networks.

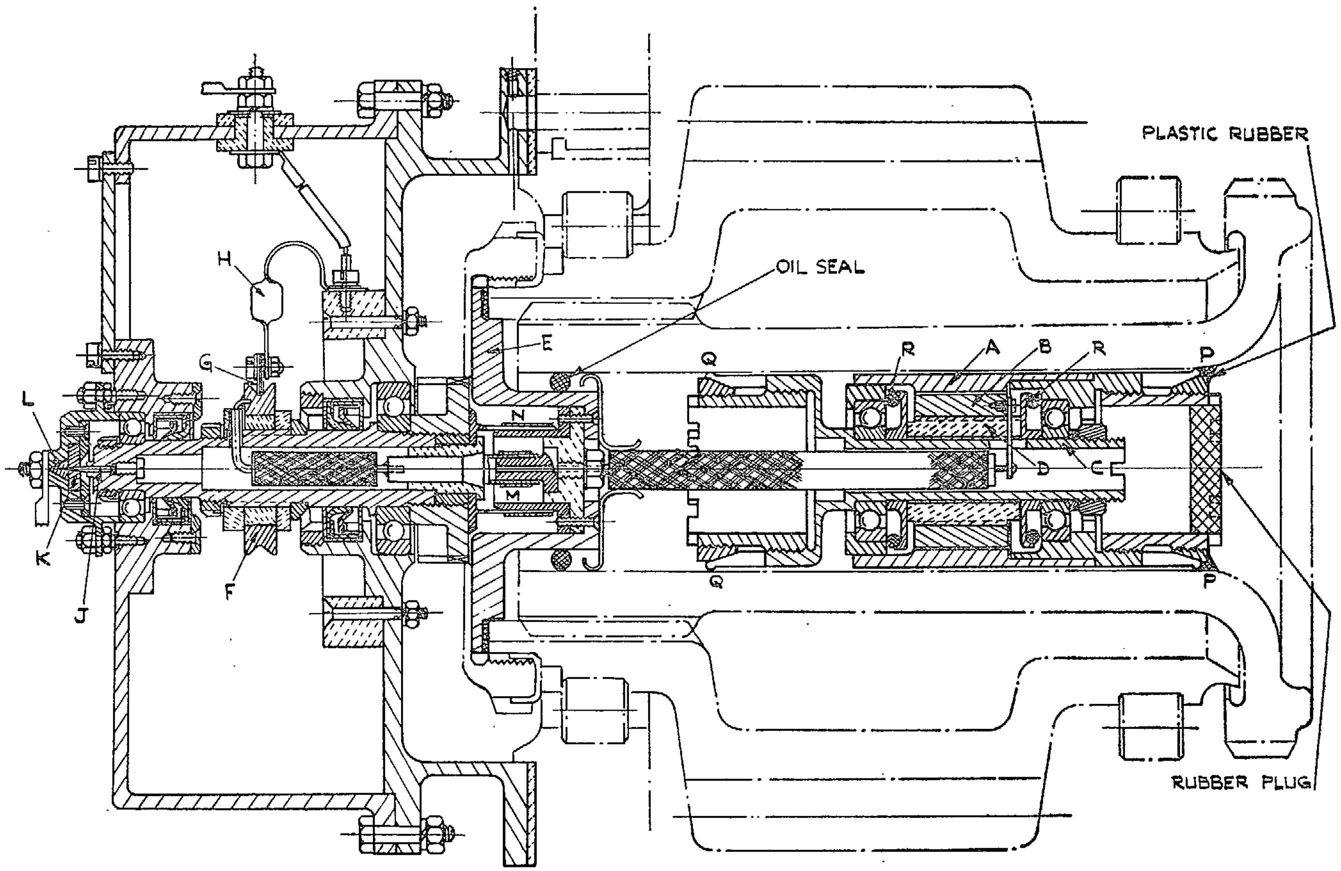


Fig. 18a. Capacity torsiograph.

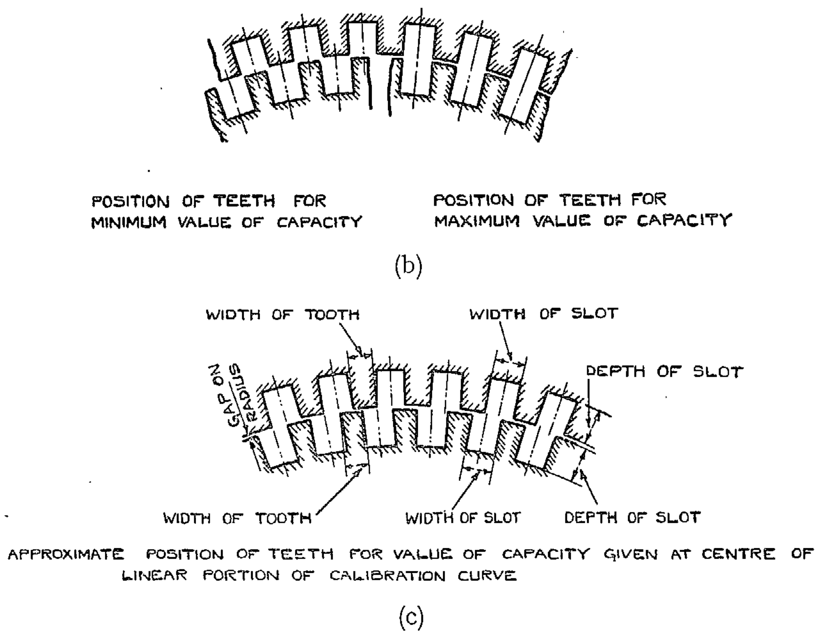


FIG. 18b and c. Enlarged view of serrations of R.A.E. capacity torsiograph.

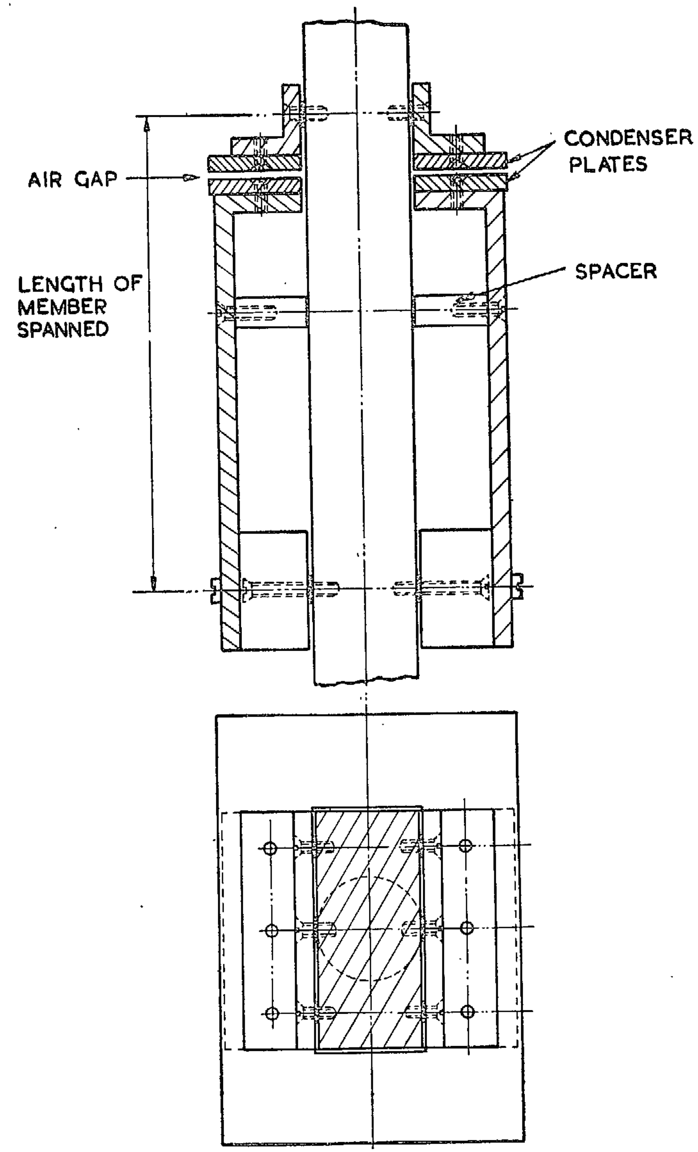


FIG. 19. Variable capacity force pick-up.

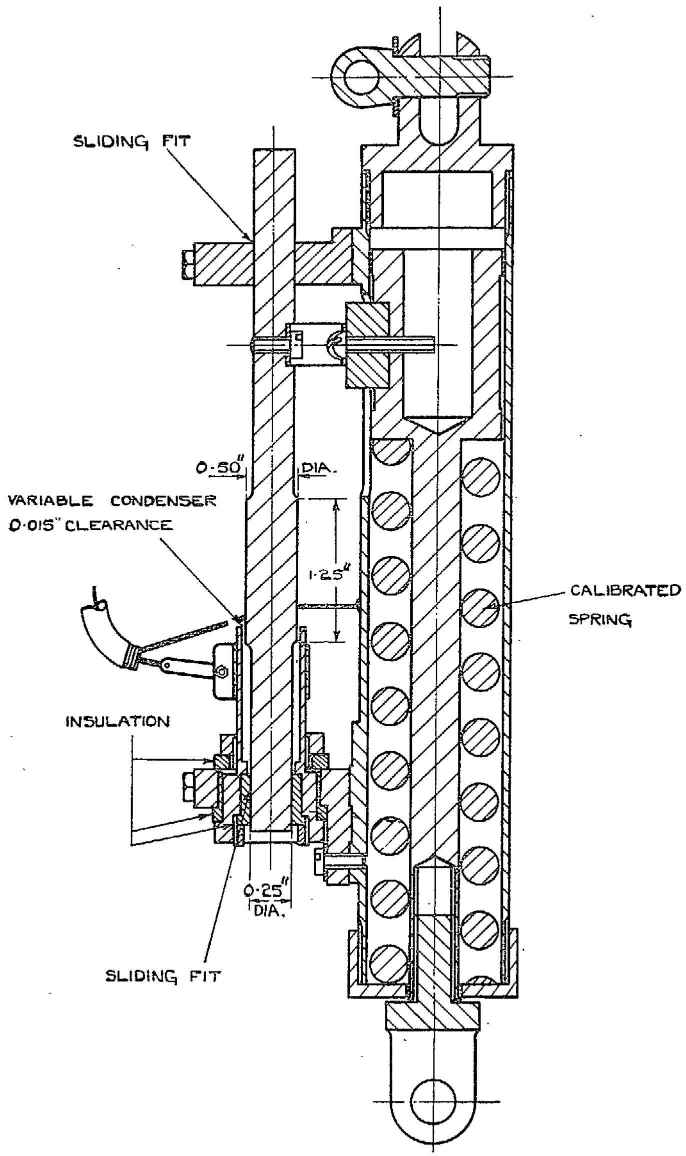
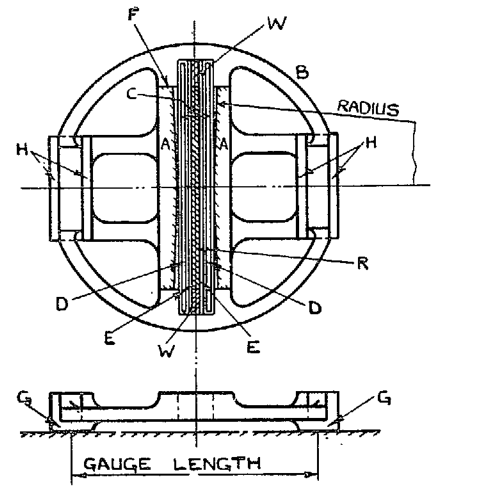
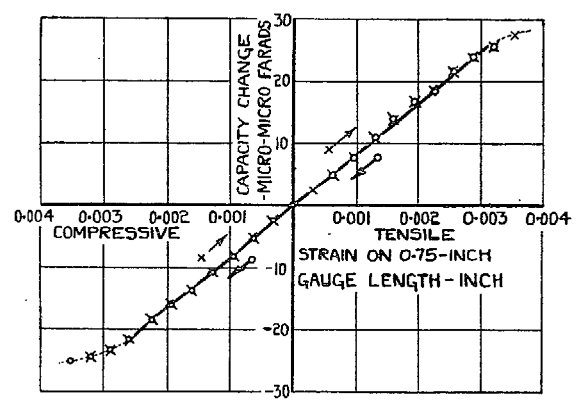


FIG. 20. Force pick-up—for glider tow rope.



Multiple plate capacity type strain gauge.



Calibration curve of multiple plate capacity strain gauge

FIG. 21. Range of linearity 0·005; sensitivity 8·3 $\mu\mu F$ per 0·001 in. strain; gauge length of element 0·75 in.

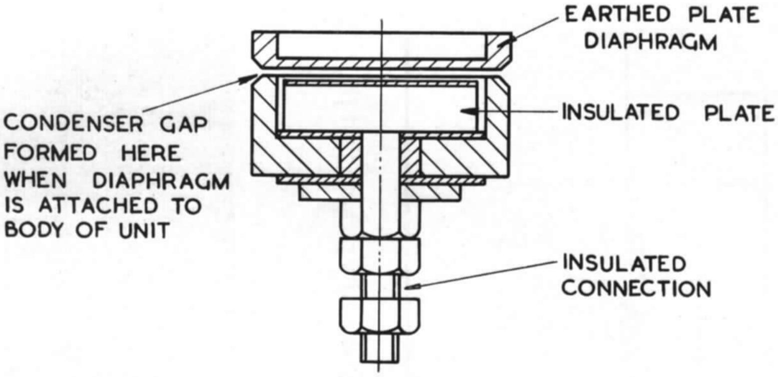


FIG. 22. Basic form of variable capacity pressure pick-up.

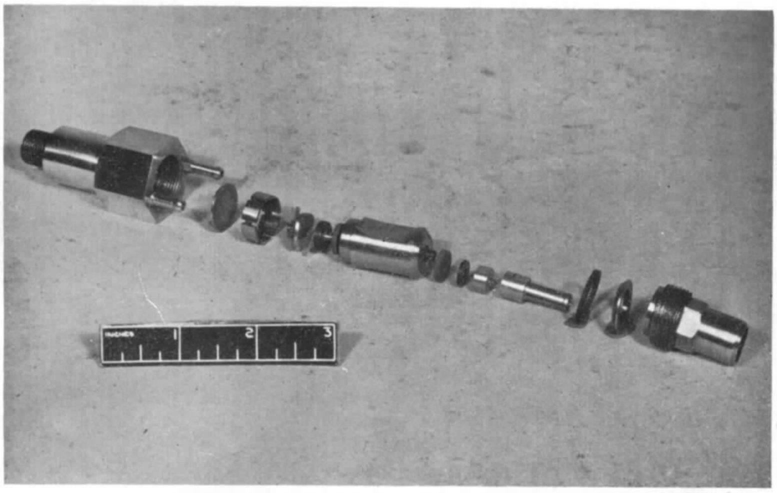


FIG. 23. Water cooled capacity type pressure pick-up unit (R.A.E.).

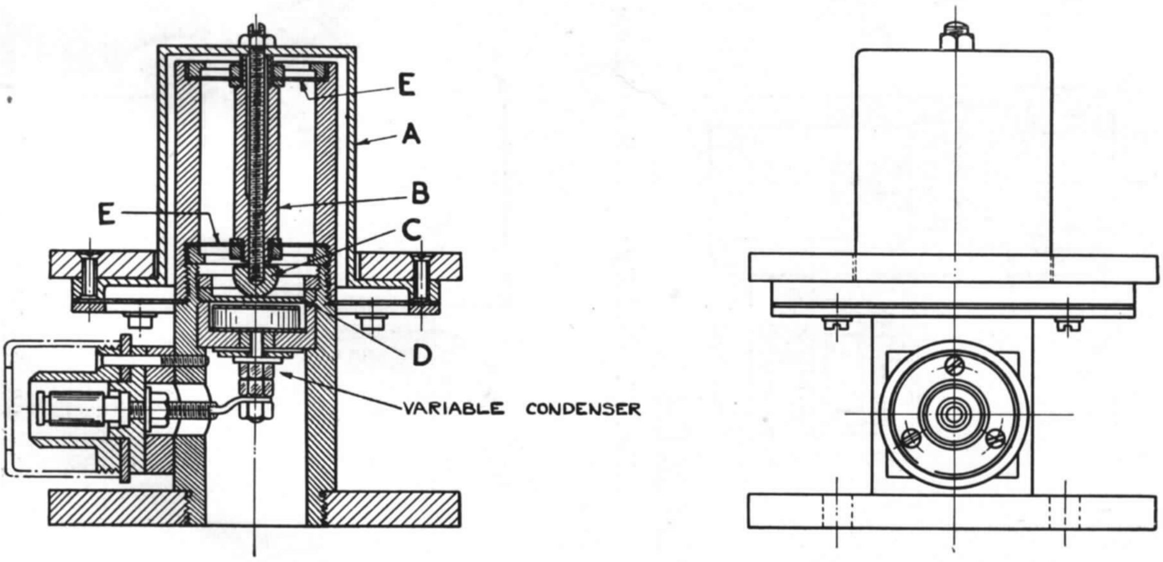


FIG. 24. Variable capacity type acceleration pick-up (low g).

G2

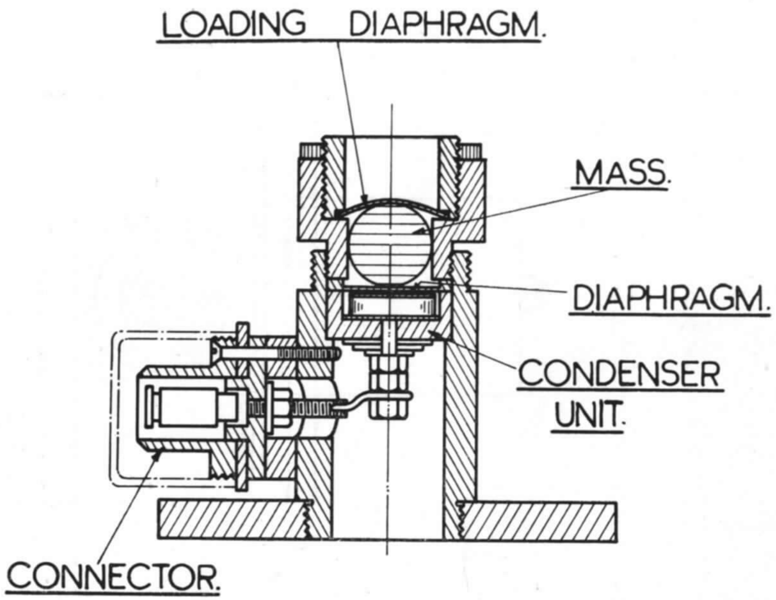


FIG. 25. Capacity acceleration pick-up, type 'B'.

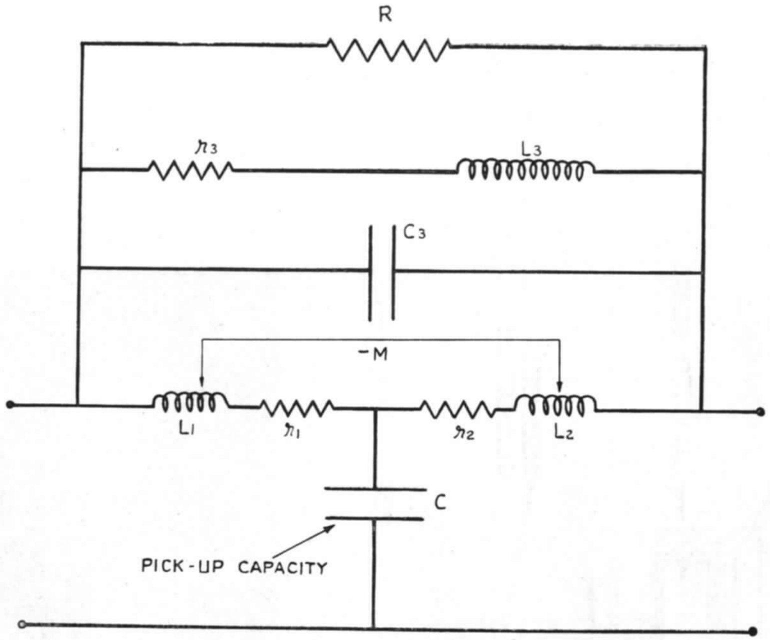


FIG. 27. Bridged-T circuit for variable capacity pick-up unit (Roess).

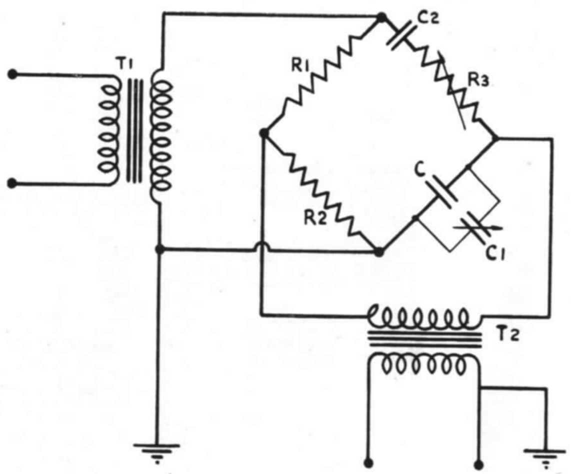


FIG. 26. Basic bridge circuit for variable capacity pick-ups.

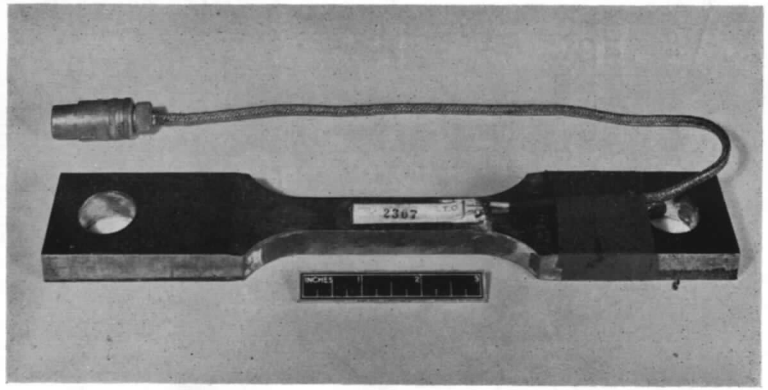
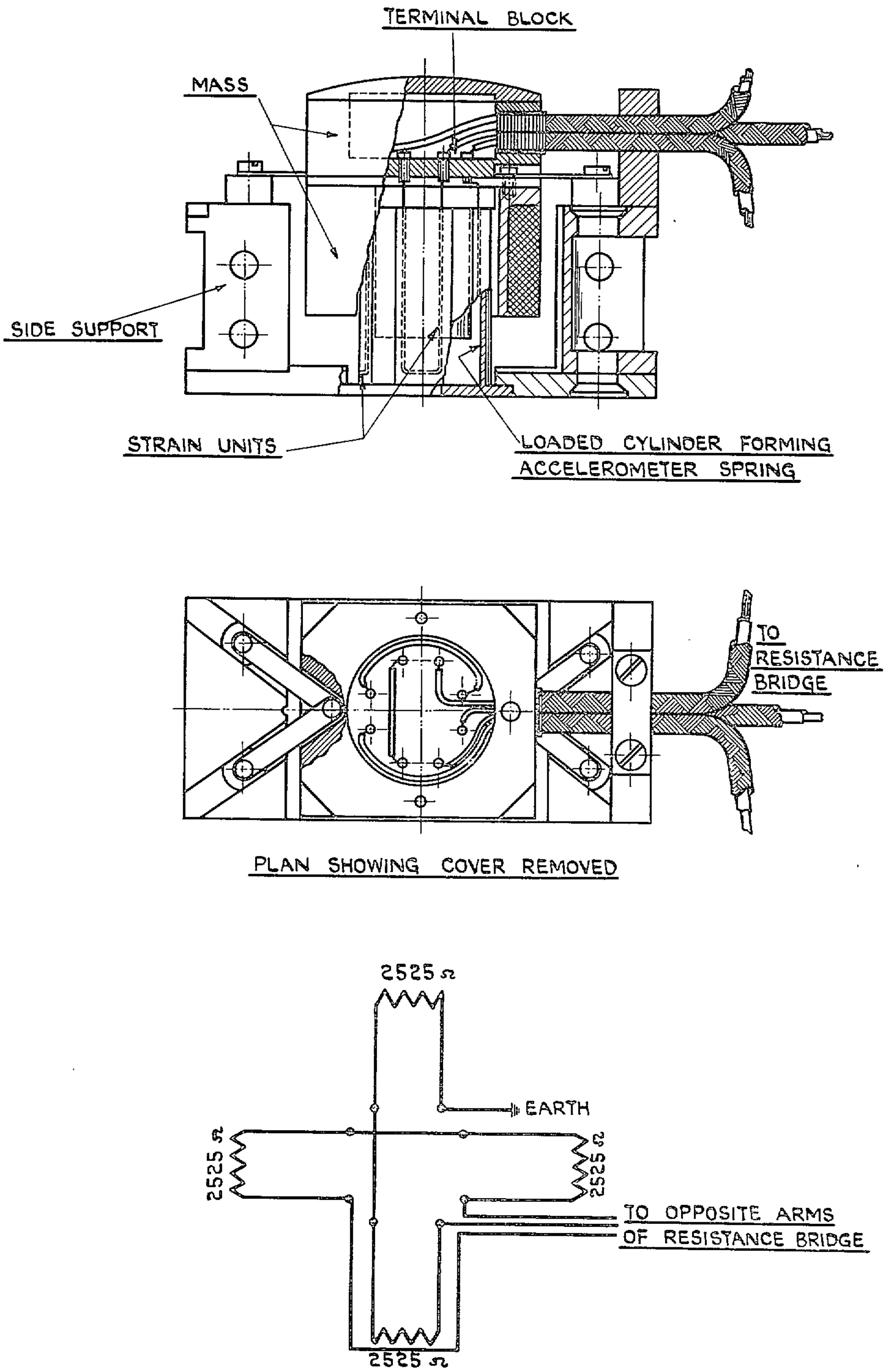


FIG. 28. Variable resistance force pick-up.



Wiring diagram

FIG. 29. R.A.E. acceleration pick-up. Mk. I (range $\pm$ 300g.).

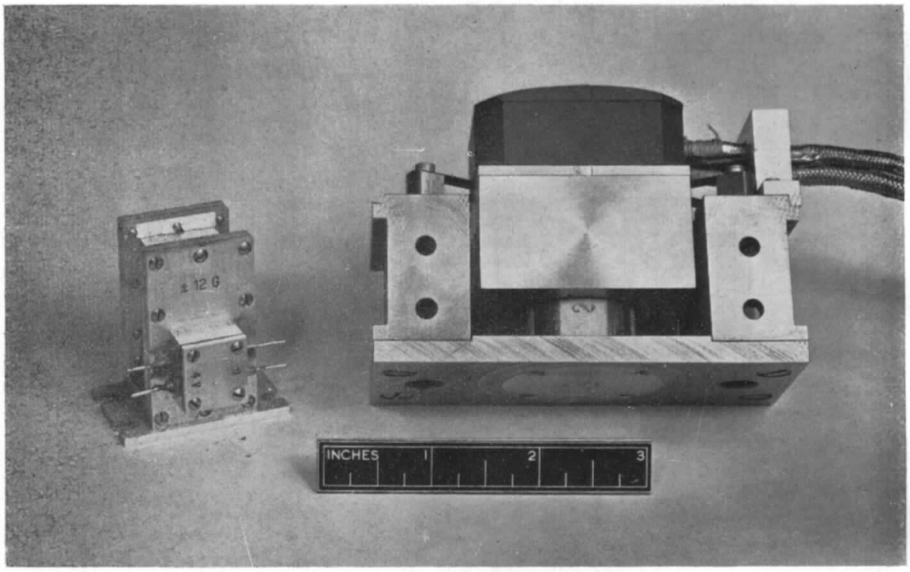


Fig. 30. Acceleration pick-ups.

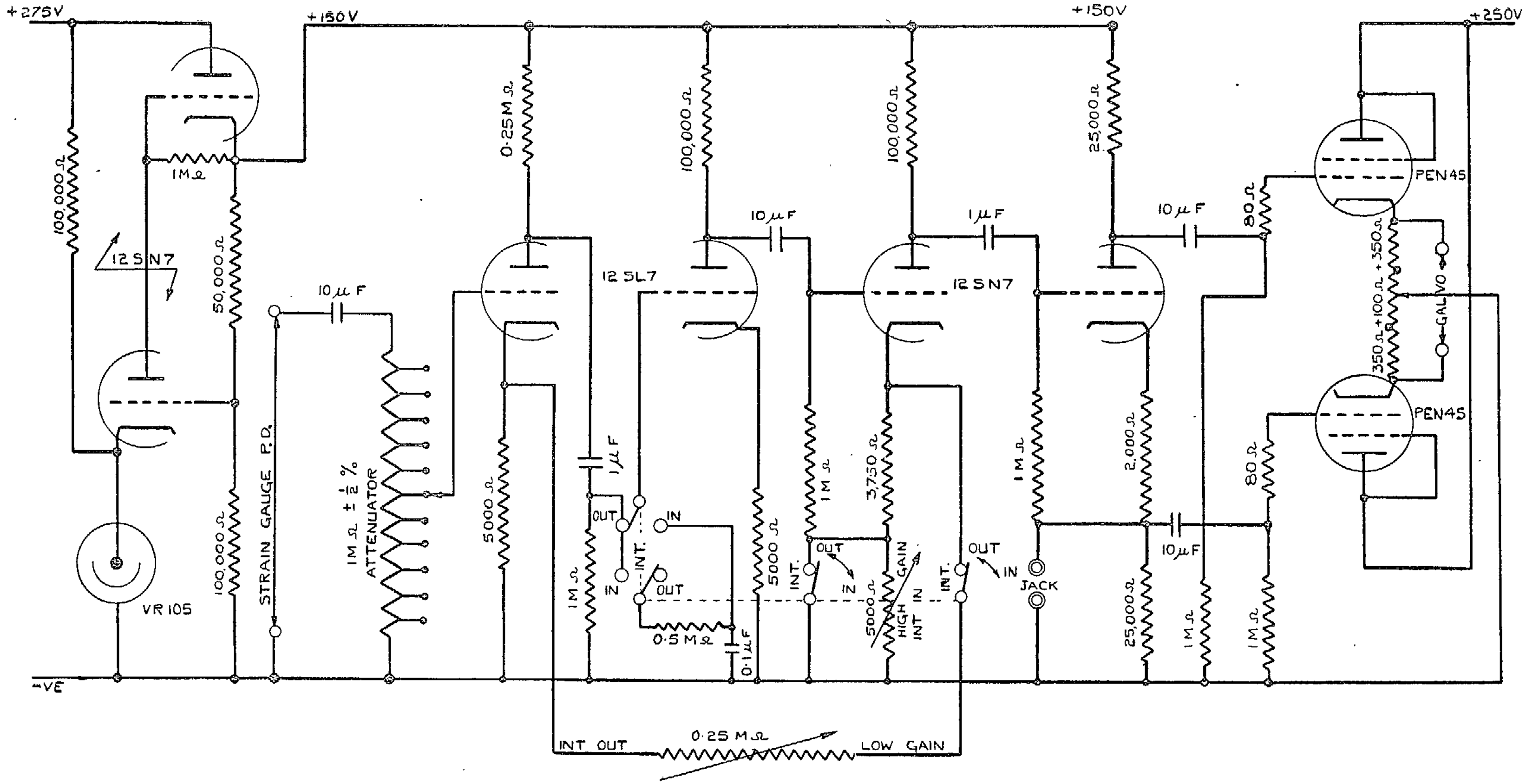


FIG. 31. Low-frequency amplifier for use with vibration galvanometer.

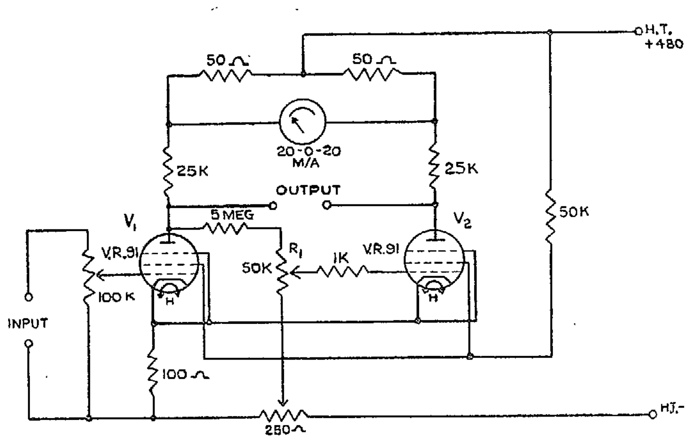


Fig. 32a. Paraphase direct coupled amplifier.

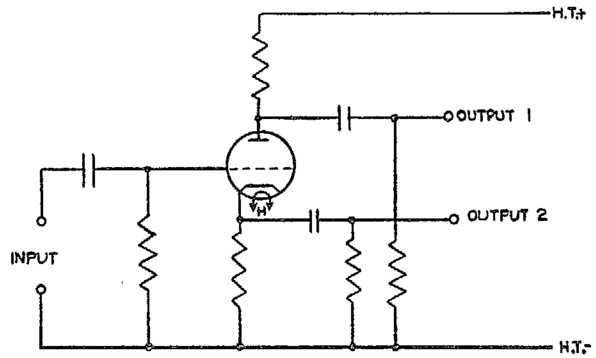


Fig. 32b. Single valve phase splitter with equal anode and cathode load.

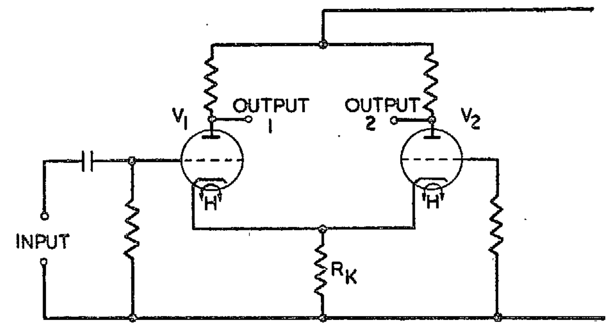


Fig. 32c. Constant potential grid method.

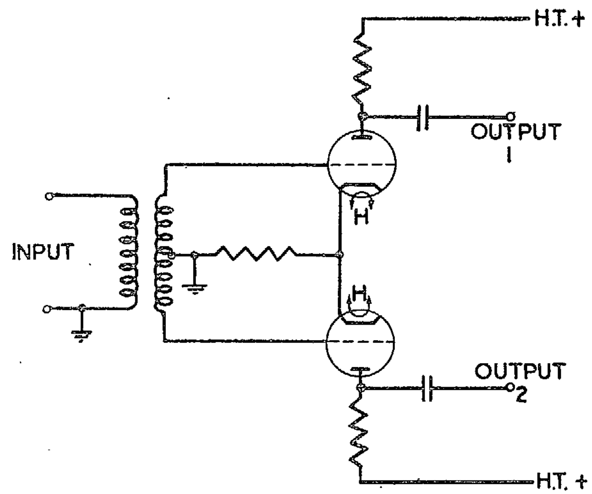


Fig. 32d. Centre tapped transformer method.

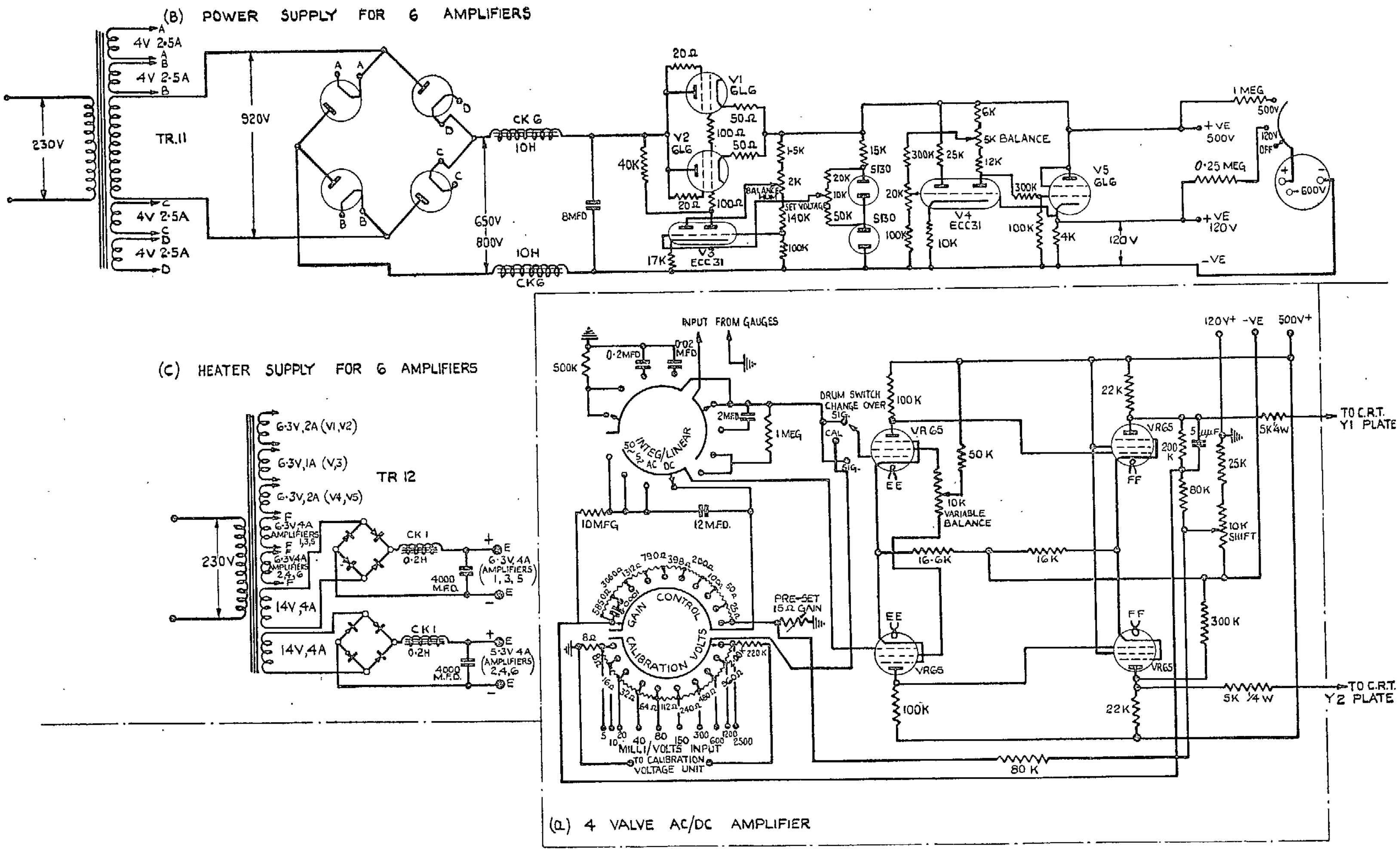


Fig. 33. Direct coupled amplifier and power pack.

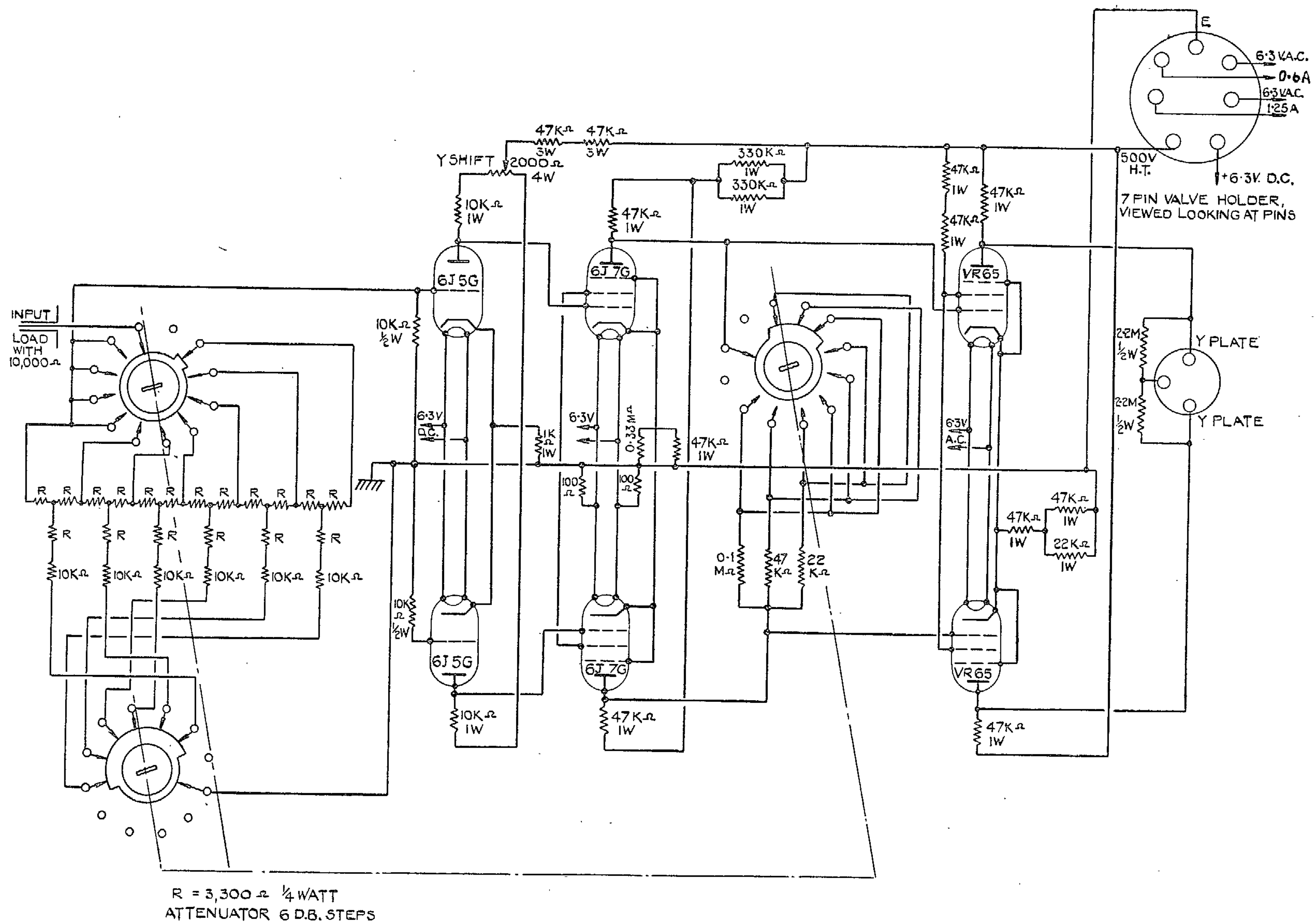


FIG. 34. Direct coupled amplifier (Plessey).

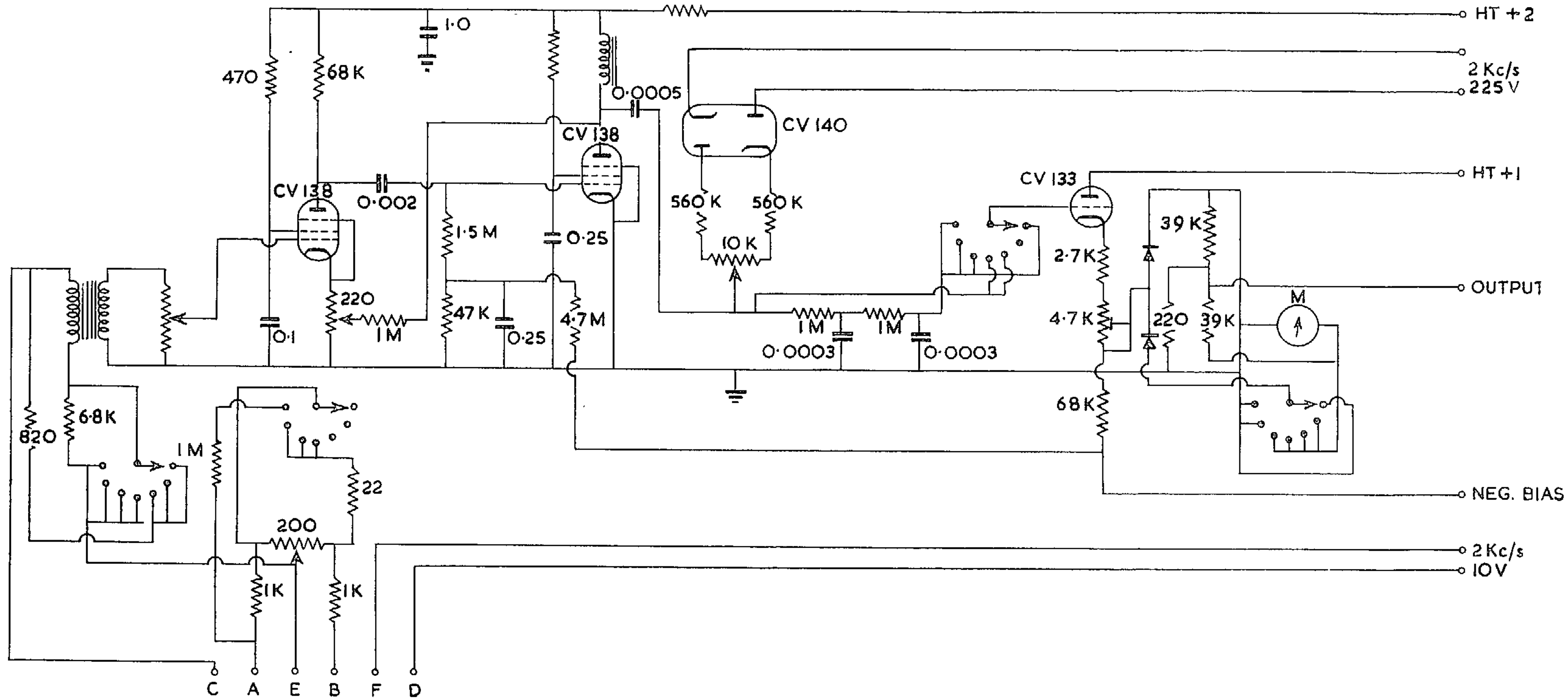
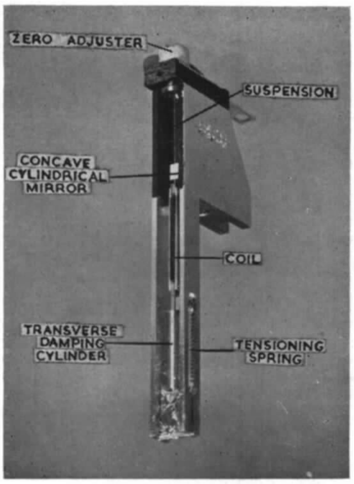


Fig. 35. Carrier amplifier and demodulator.



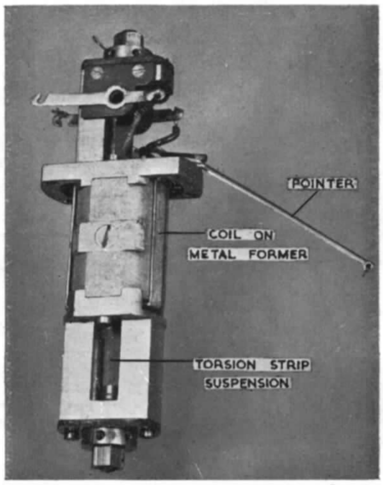


FIG. 36a. FIG. 36b. (Henry Hughes)

Electromagnetic vibration galvanometers.

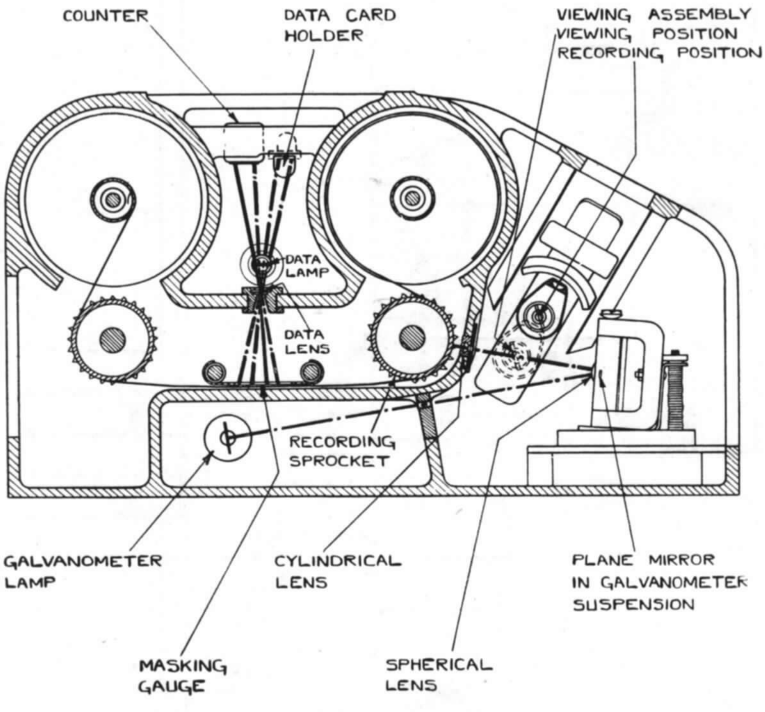


FIG. 37. Diagram of vibration galvanometer camera showing optical system.

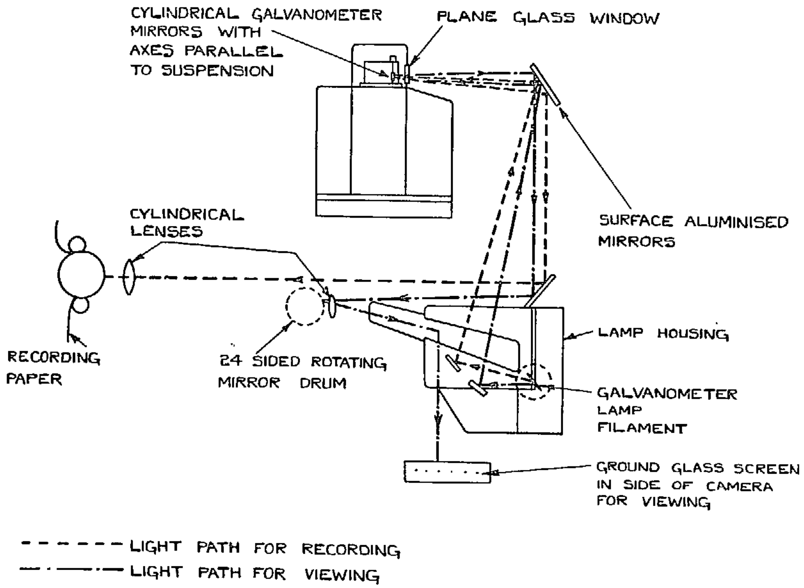


FIG. 38. Optical system of six channel vibration galvanometer camera.

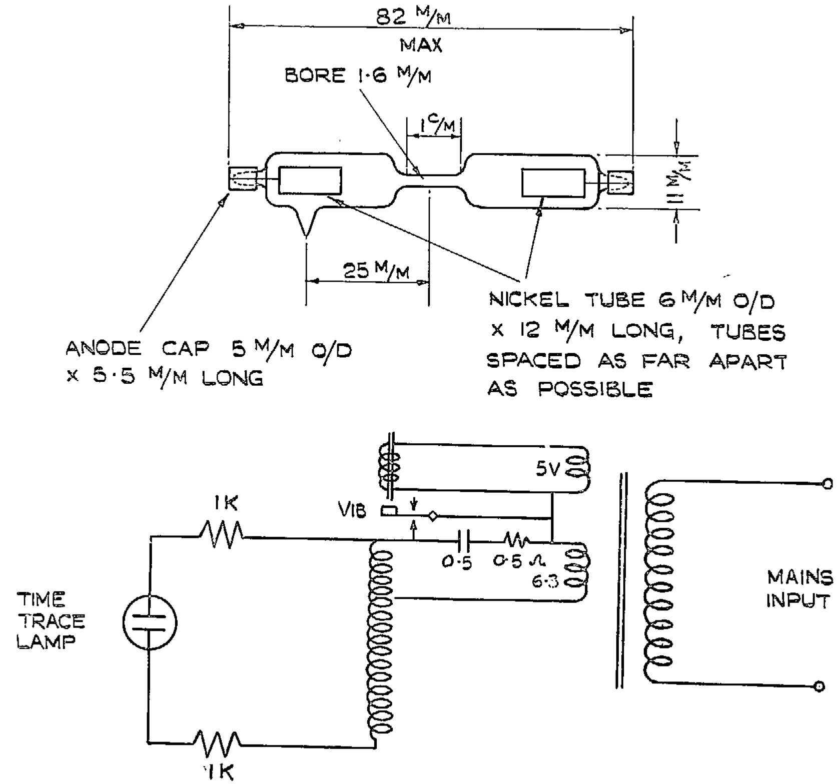


FIG. 39. Discharge lamp type T.N.1. and circuit.

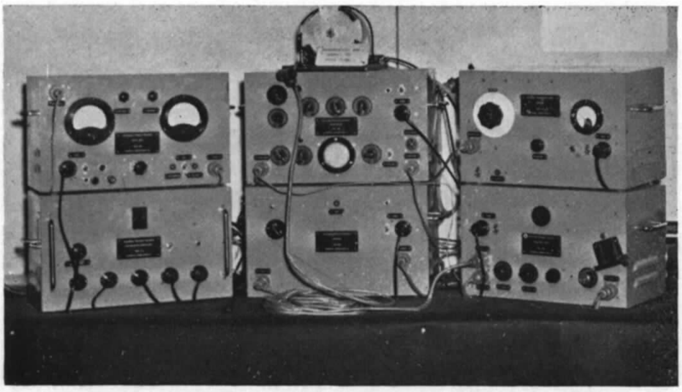


FIG. 40. Wind tunnel pressure recorder.

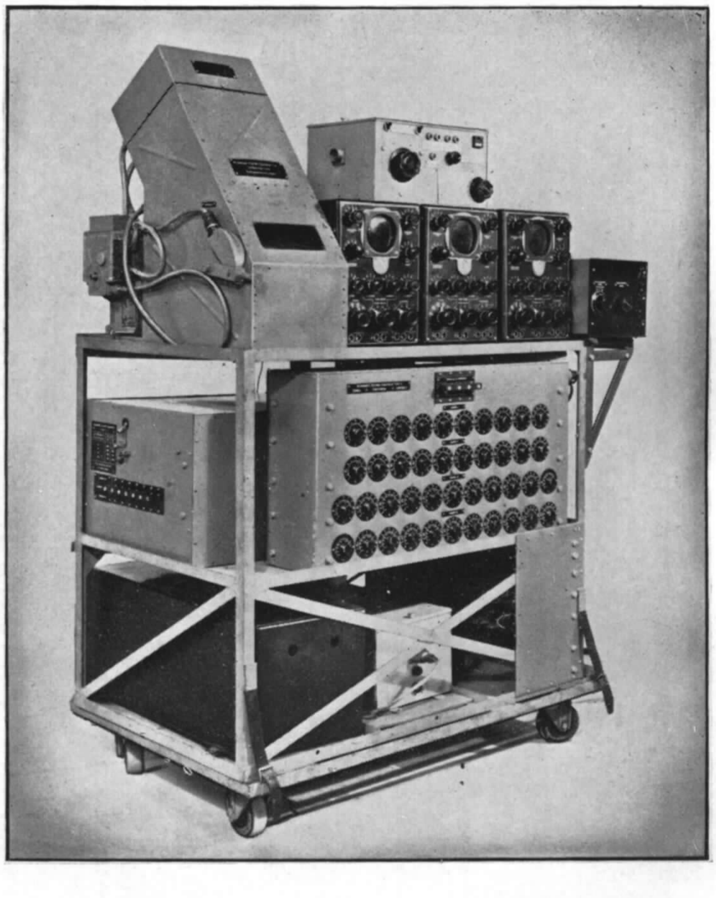


FIG. 41. Resonance testing equipment.

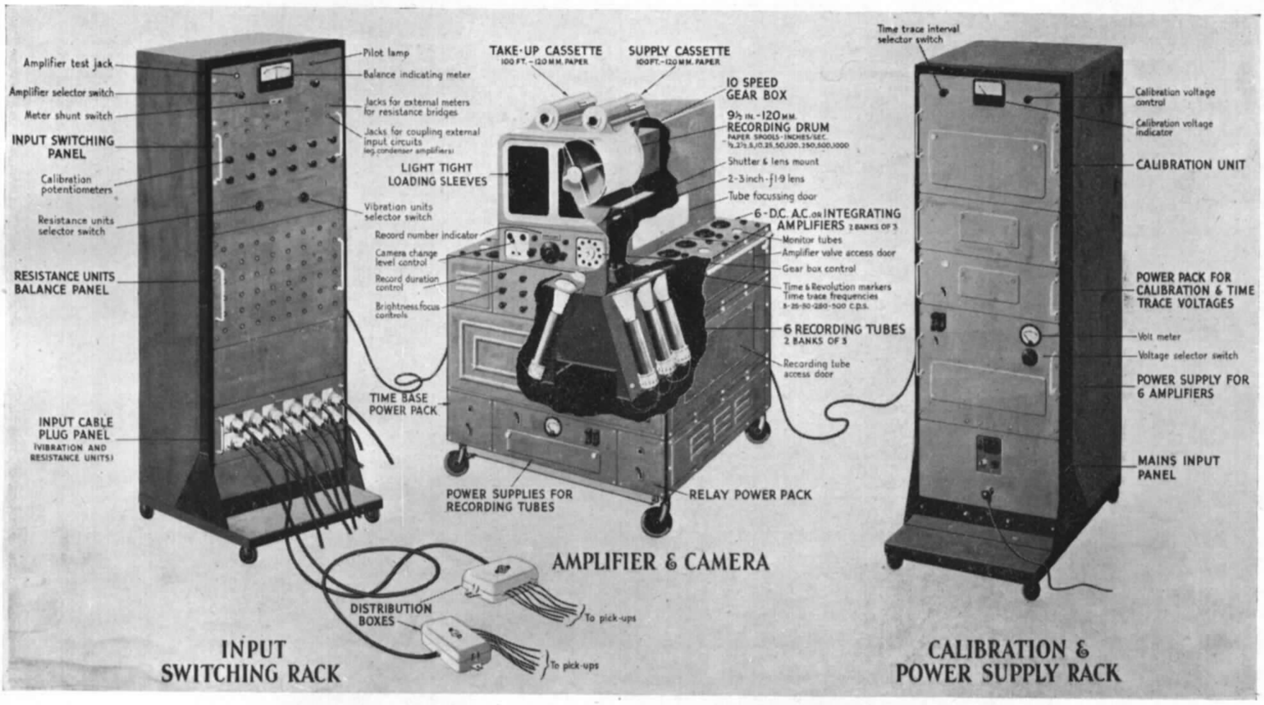


FIG. 42. Six channel cathode-ray oscillograph recording equipment (Mark I).

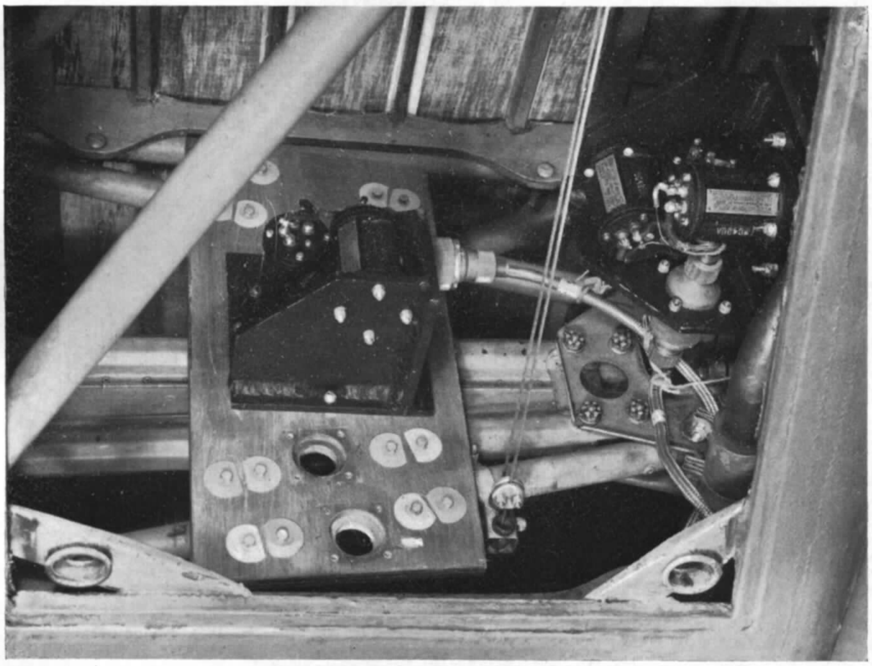


FIG. 43. Installation of vibration pick-ups in *Hurricane*.

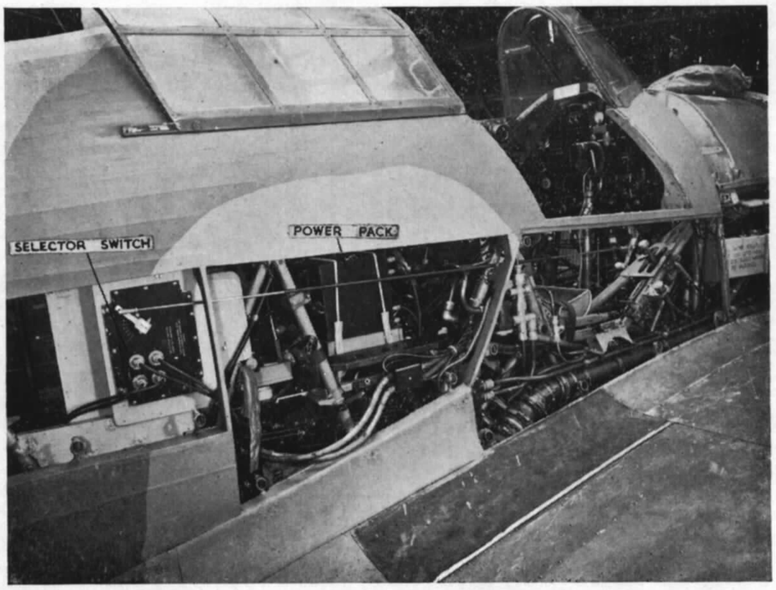


FIG. 44. Starboard side view.

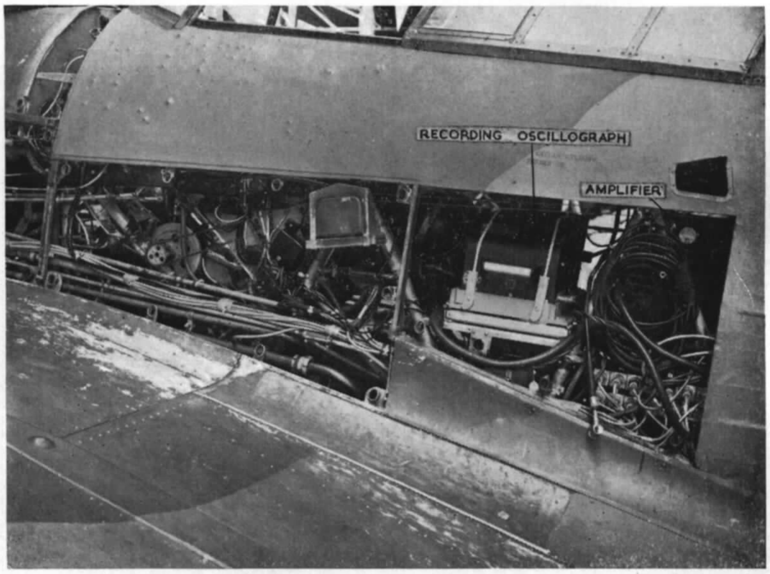


FIG. 45. Port side view.

Installation of vibration recording equipment in *Hurricane*.

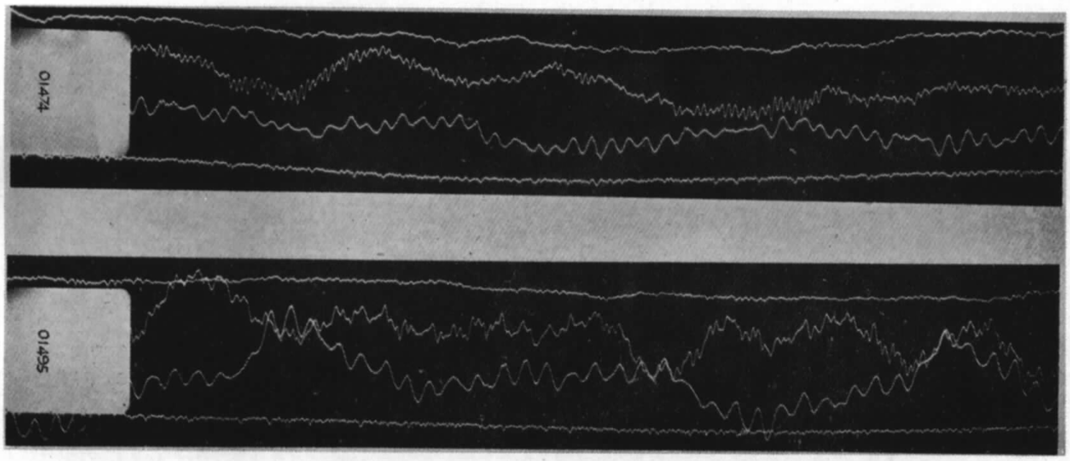


FIG. 46. Vibration characteristics of *Hurricane* in flight.

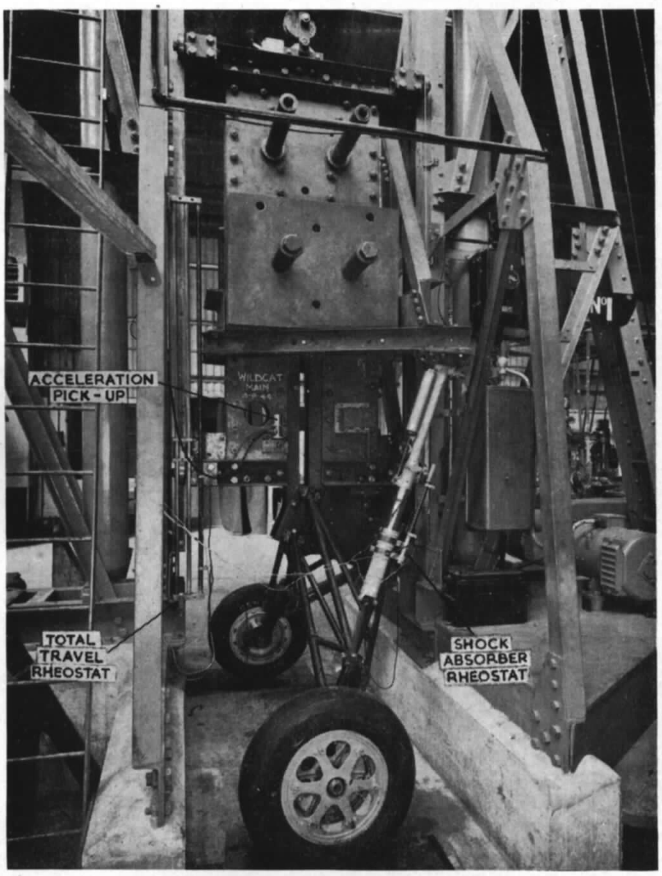


FIG. 47. Undercarriage drop testing installation.

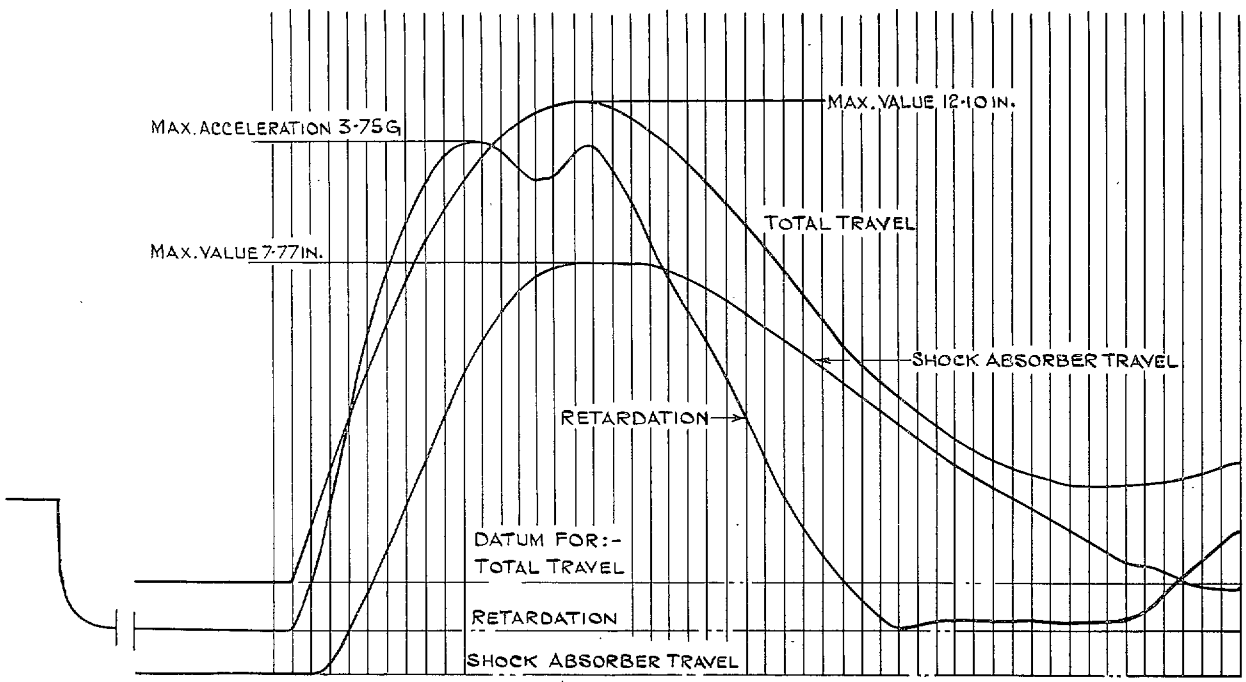


FIG. 48. Typical record taken during an undercarriage drop test.

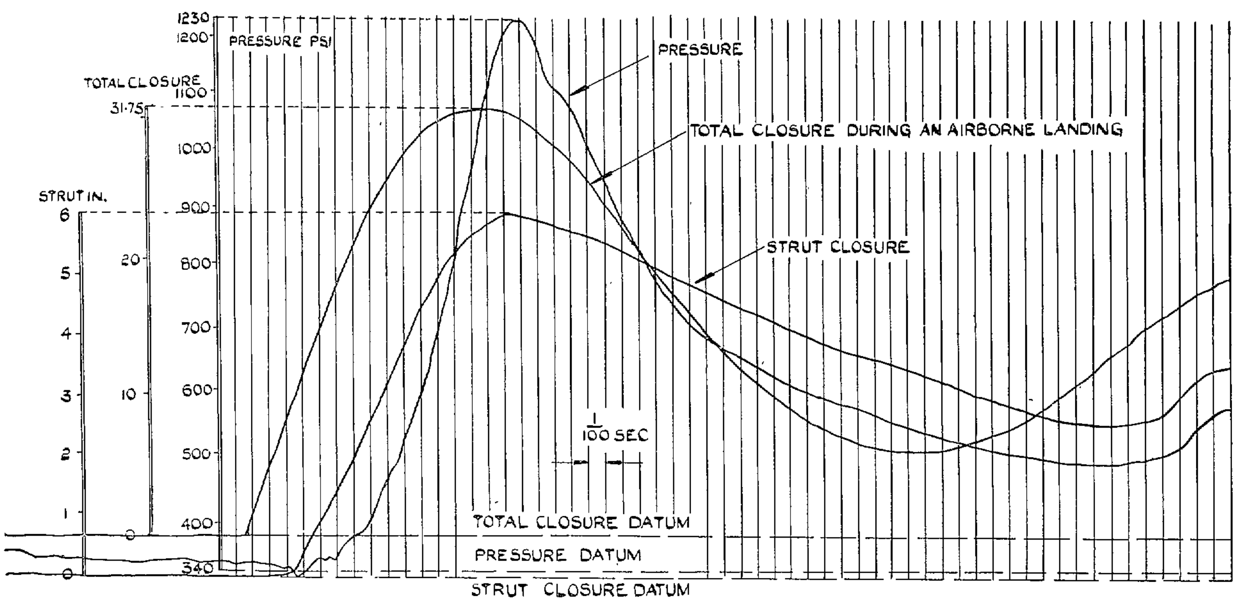


FIG. 49. Windsor T.W. unit. Variation of air pressure.

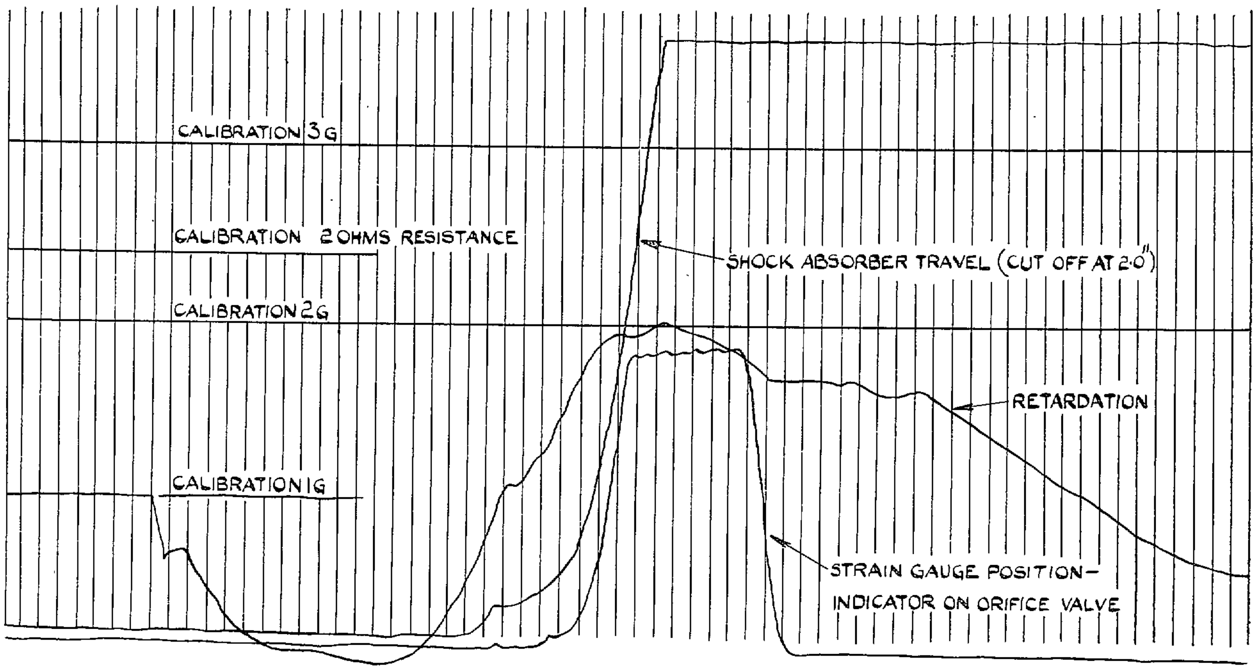


FIG. 50. Drop test on Fairey *Spearfish* undercarriage to check behaviour of orifice valve at low velocities.

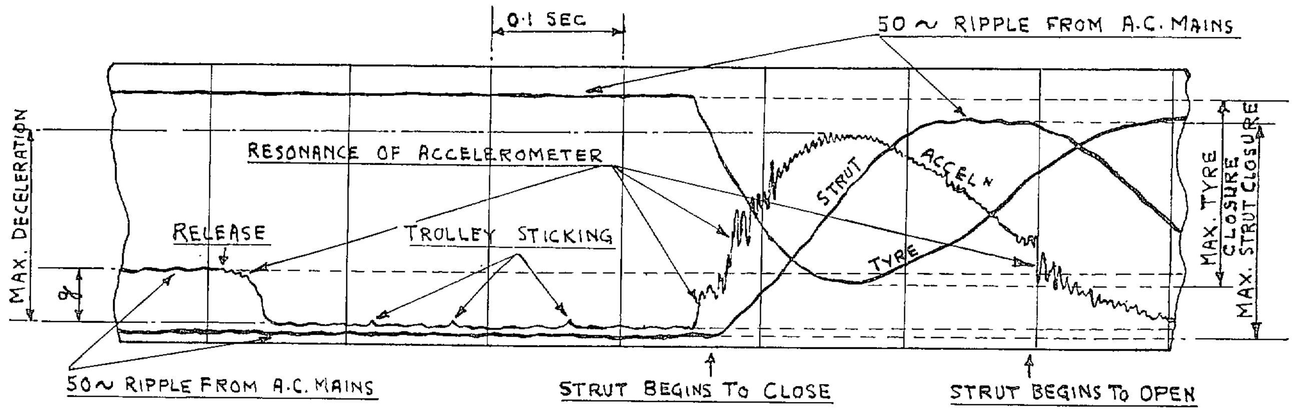


FIG. 51. Tracing of drop test records.

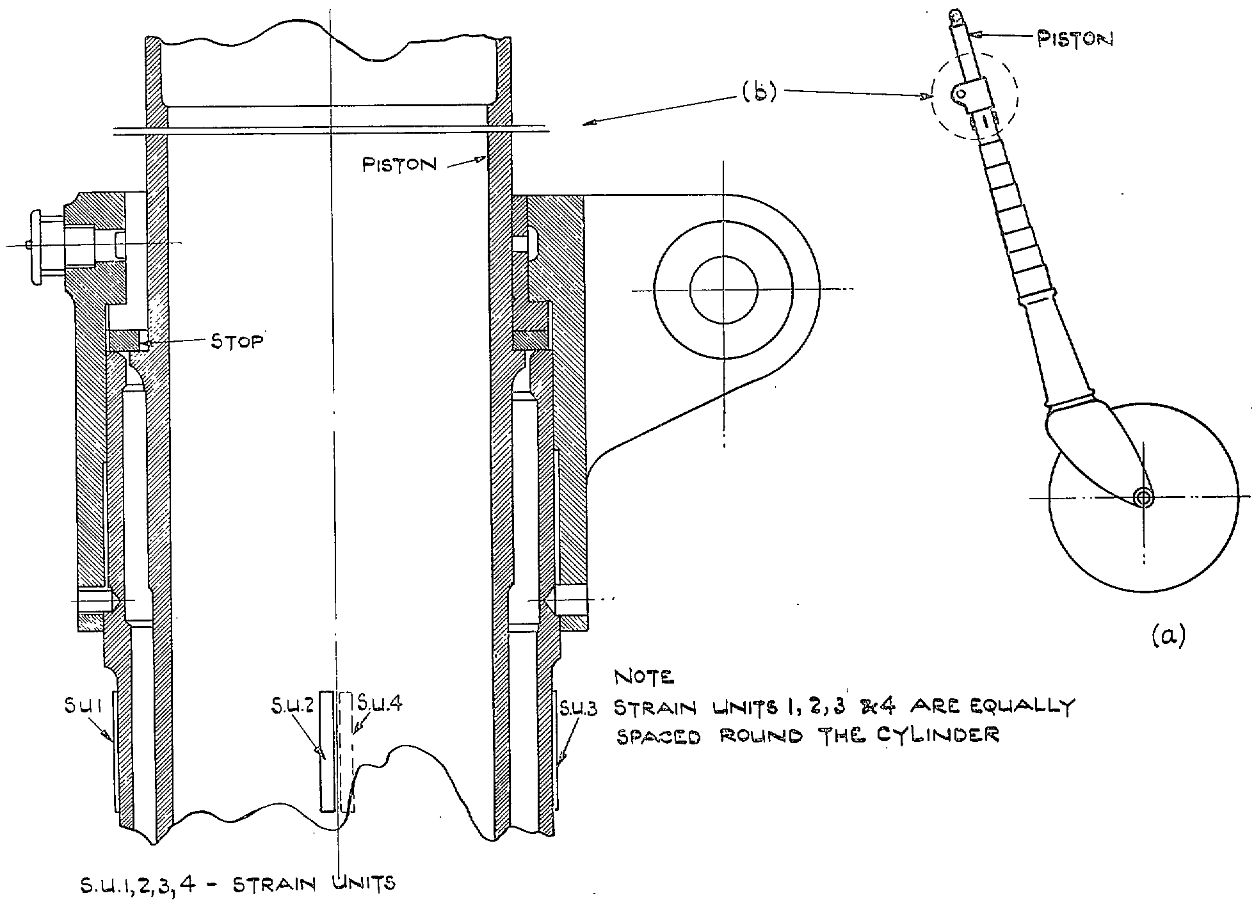


FIG. 52. Diagrams showing strain units on *Halifax* tail wheel shock absorber.

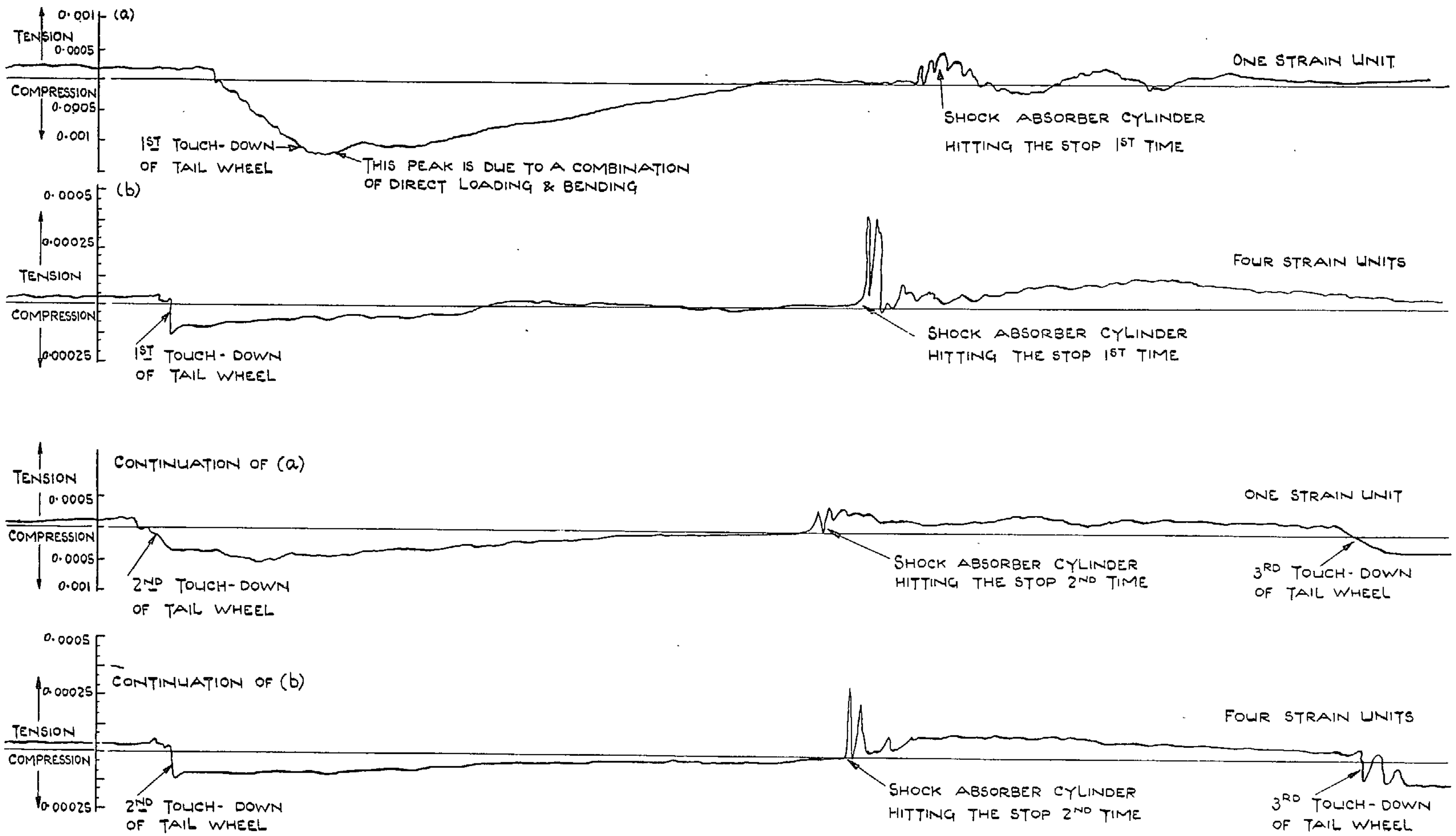
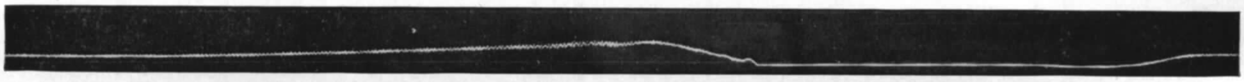


FIG. 53. Strain variations on *Halifax* tail wheel shock absorber cylinder due to butting the stop on run out.

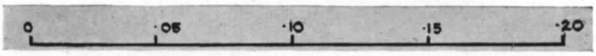
Test 2. Speed 2,600 r.p.m. Capacity 16 cu in. Peak pressure 4,550lb/sq in.



Test 5. Speed 2,600 r.p.m. Capacity 43 cu in. Peak pressure 3,800lb/sq in.

Test 8. Speed 2,600 r.p.m. Capacity 177 cu in. Peak pressure 2,600lb/sq in.

Test 11. Speed 2,600 r.p.m. Capacity 288 cu in. Peak pressure 2,550lb/sq in.



Time scale—sec.
FIG. 54. Tests on Live Line pumps.

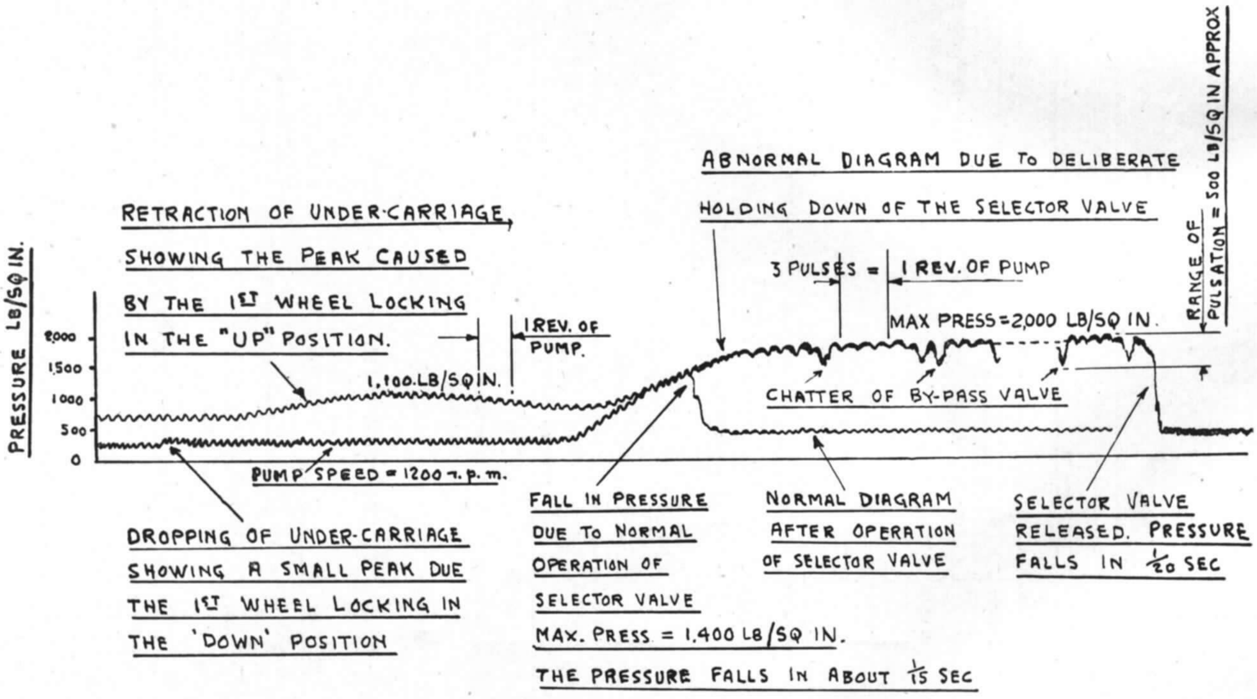


FIG. 55. Composite tracing from photographic records of pump delivery pressures taken on a Mark IV pump.

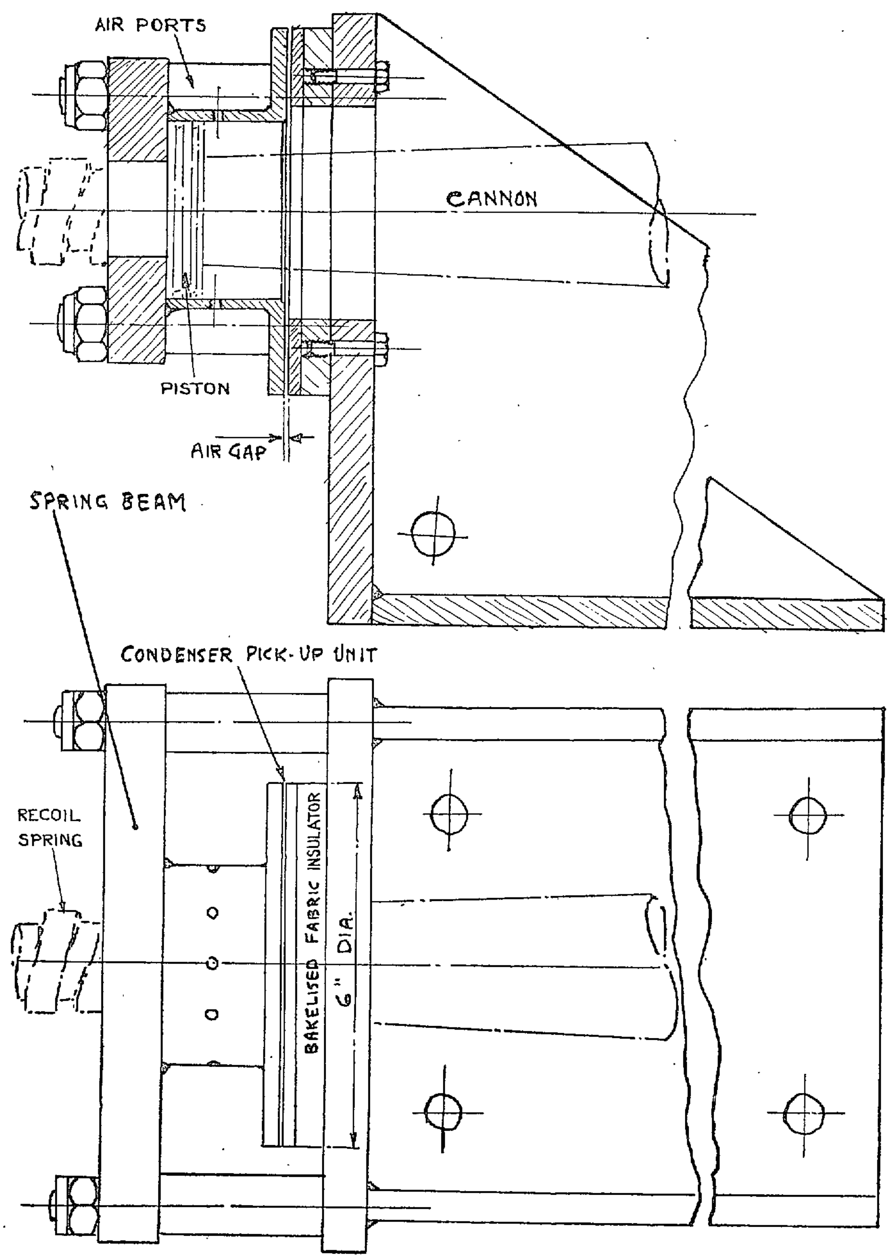


FIG. 56. Front mounting for 20 mm Hispano gun.

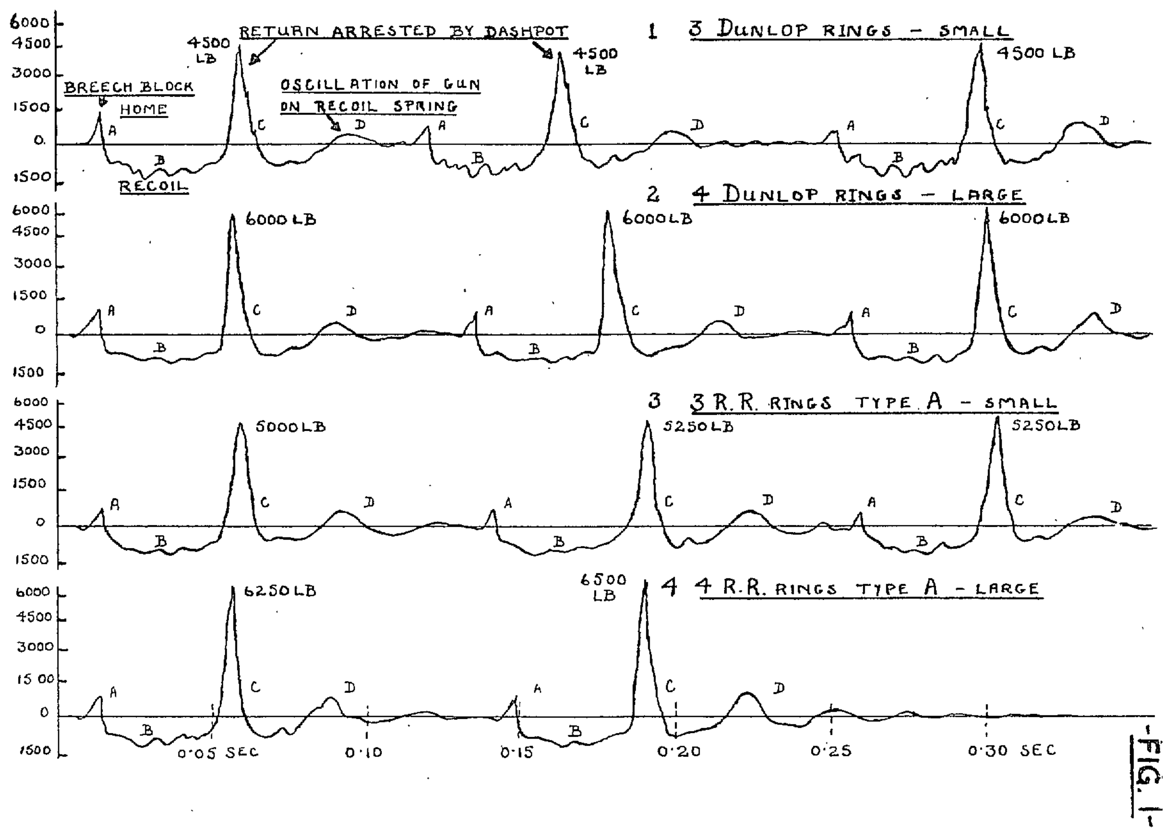


FIG. 57. Hispano 20 mm cannon. Loads on front mounting for various rubber buffers. All records taken with new rigid mounting and bevel gear feed. (Sheet I).

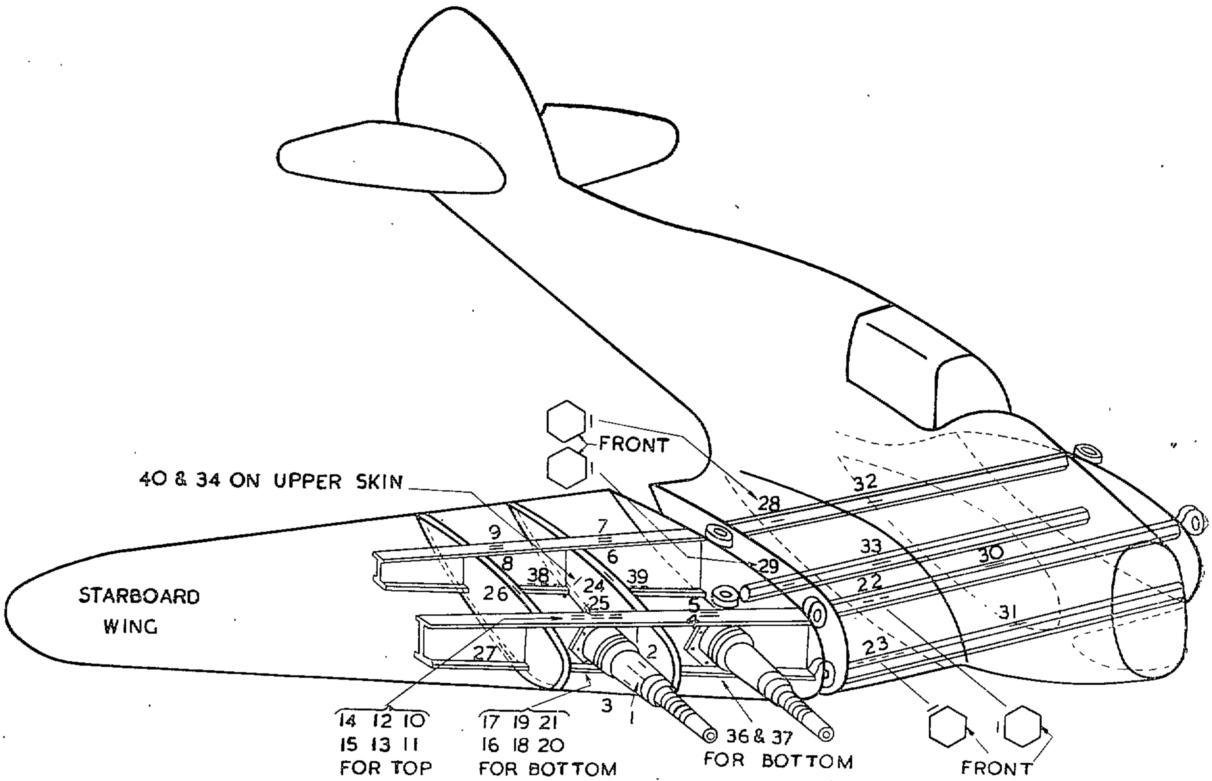


FIG. 58. Diagram showing positions of strain units on a *Hurricane*.

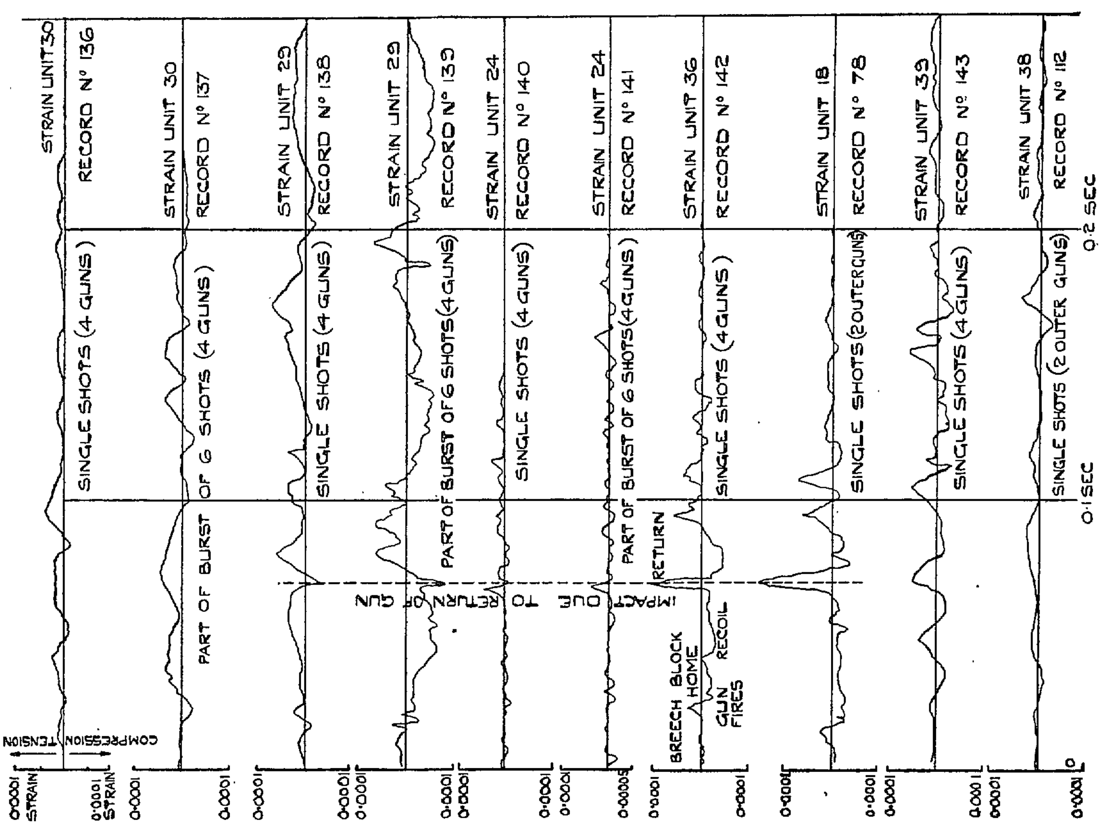


FIG. 59. Strain measurements on *Hurricane* for various conditions of firing 20 mm Hispano cannon.

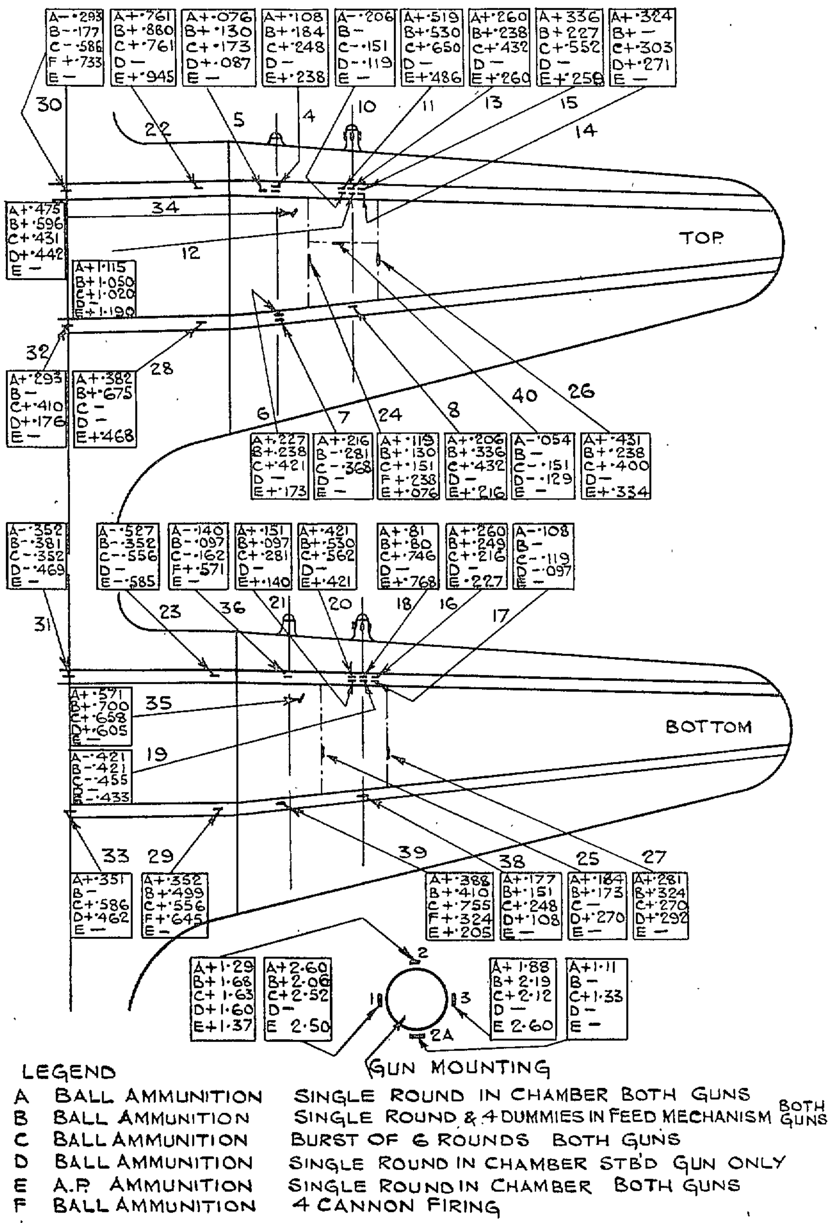


FIG. 60. Stresses in ton/sq in. caused in a *Hurricane* wing by firing 20 mm Hispano cannon.

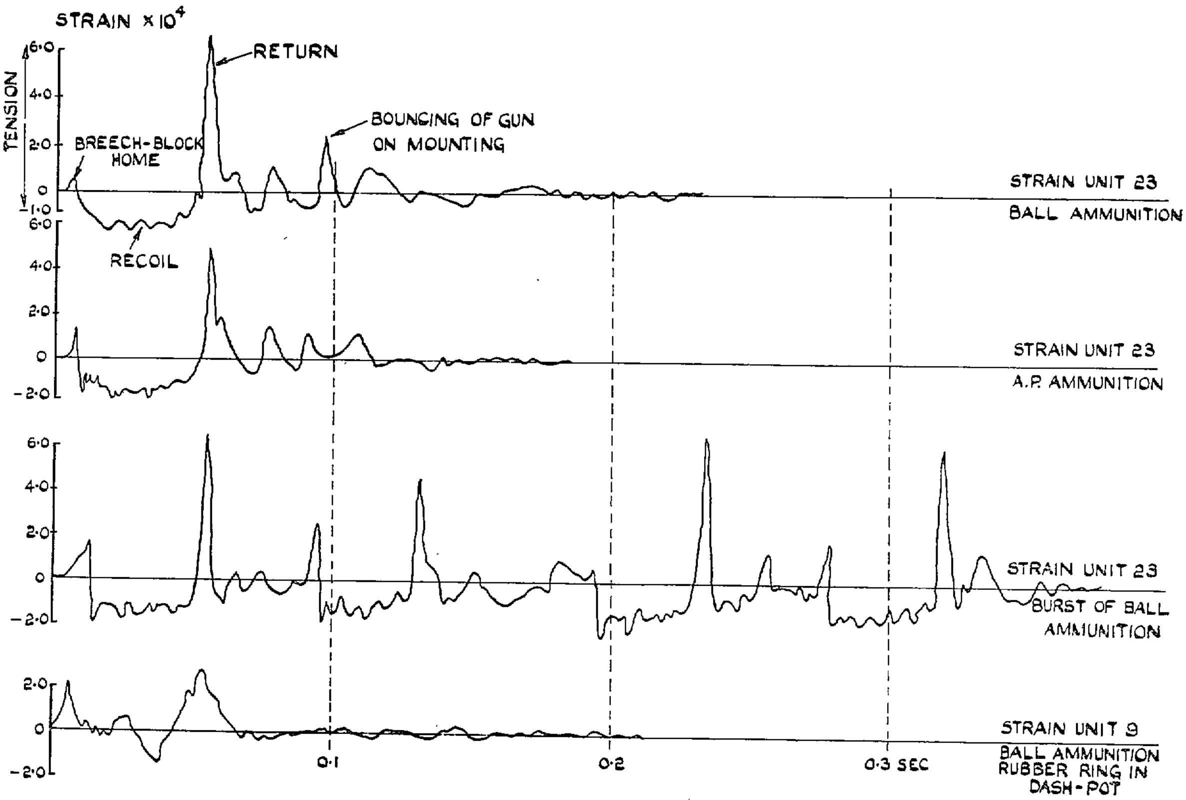
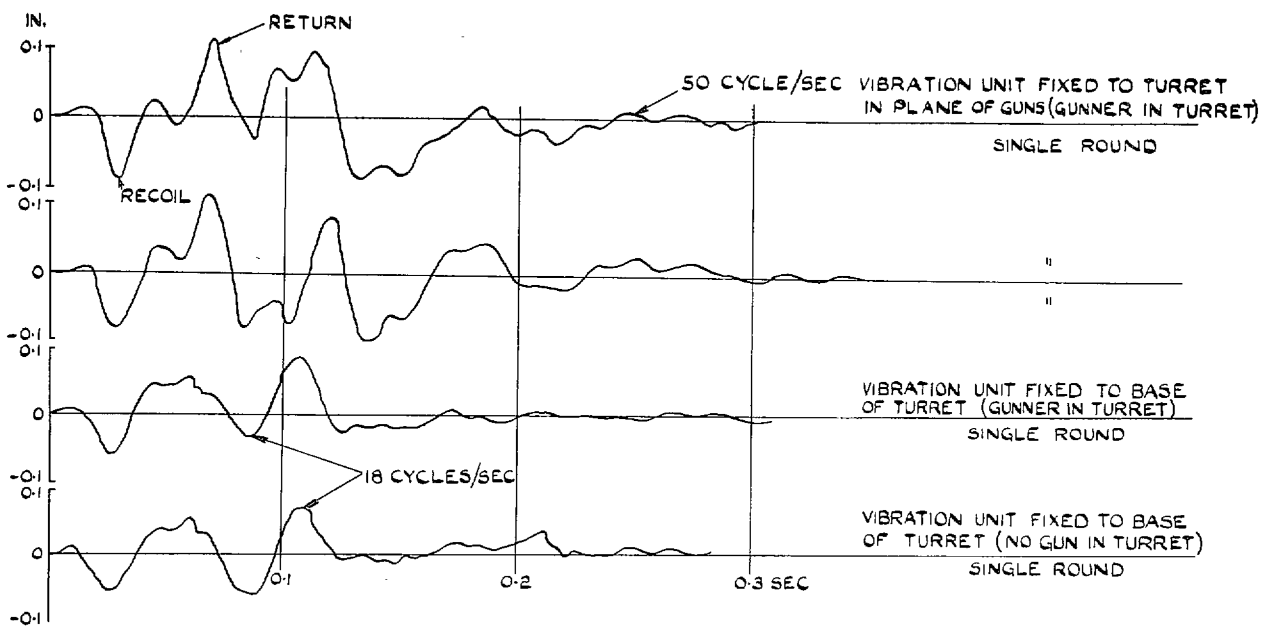


FIG. 61. Strain measurements during firing of the 20 mm Hispano cannon installed in the *Lancaster* mid-turret Mark I.



NOTE THE TWO UPPER DIAGRAMS AND THE TWO LOWER ONES ARE SHOWN TO BE IN PHASE. THIS IS PROBABLY DUE TO THE PICK-UP UNIT DIRECTION BEING REVERSED WHEN MOVED FROM TOP TO BOTTOM OF THE TURRET.

FIG. 62. Records showing horizontal fore-and-aft vibration of the Nash and Thomson Mark II turret during the simultaneous firing of the two installed 20 mm Hispano cannon.

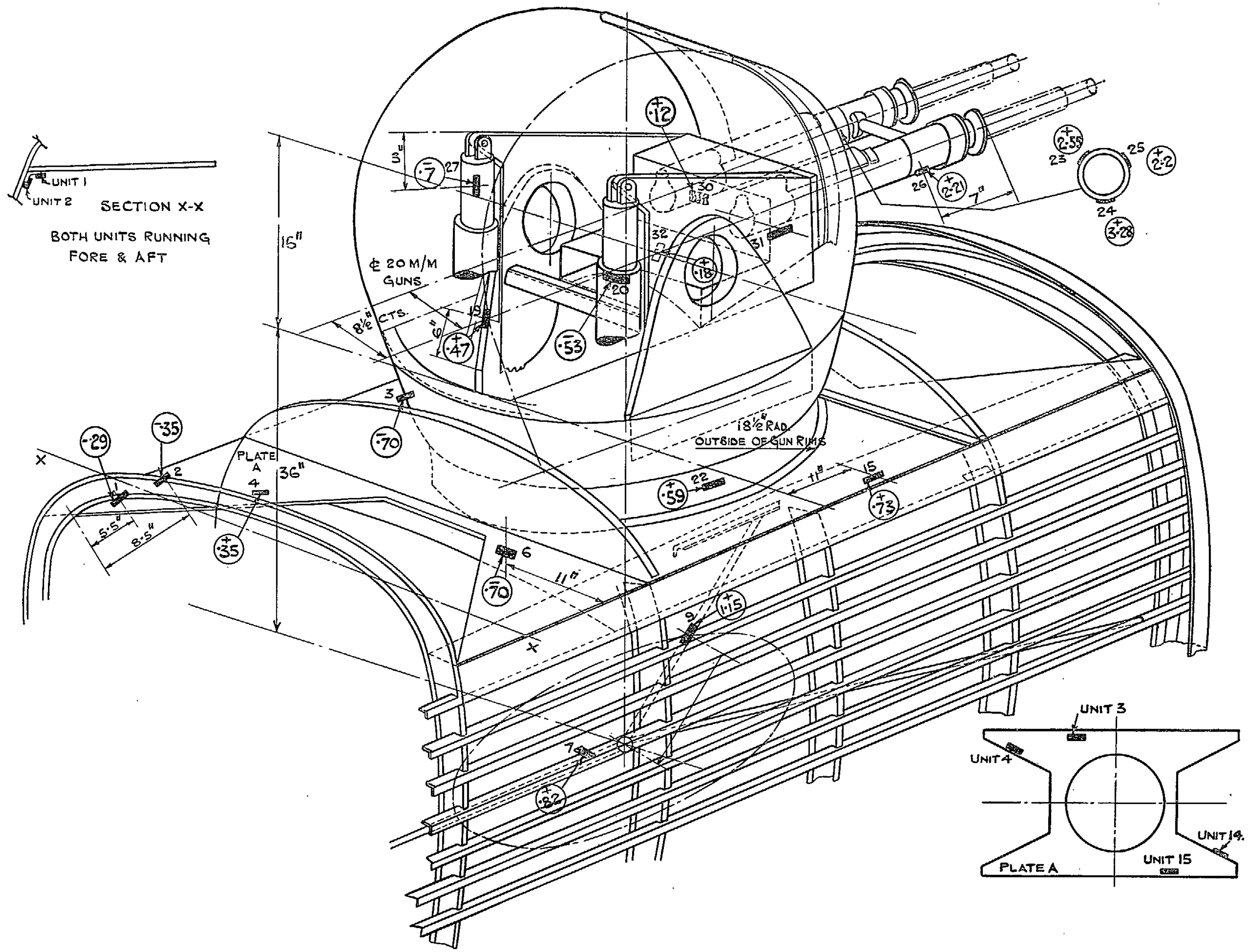


FIG. 63. Maximum stresses in *Lancaster* due to firing two 20 mm guns in the Nash and Thomson Mark II turret. Stresses given in ton/sq in.

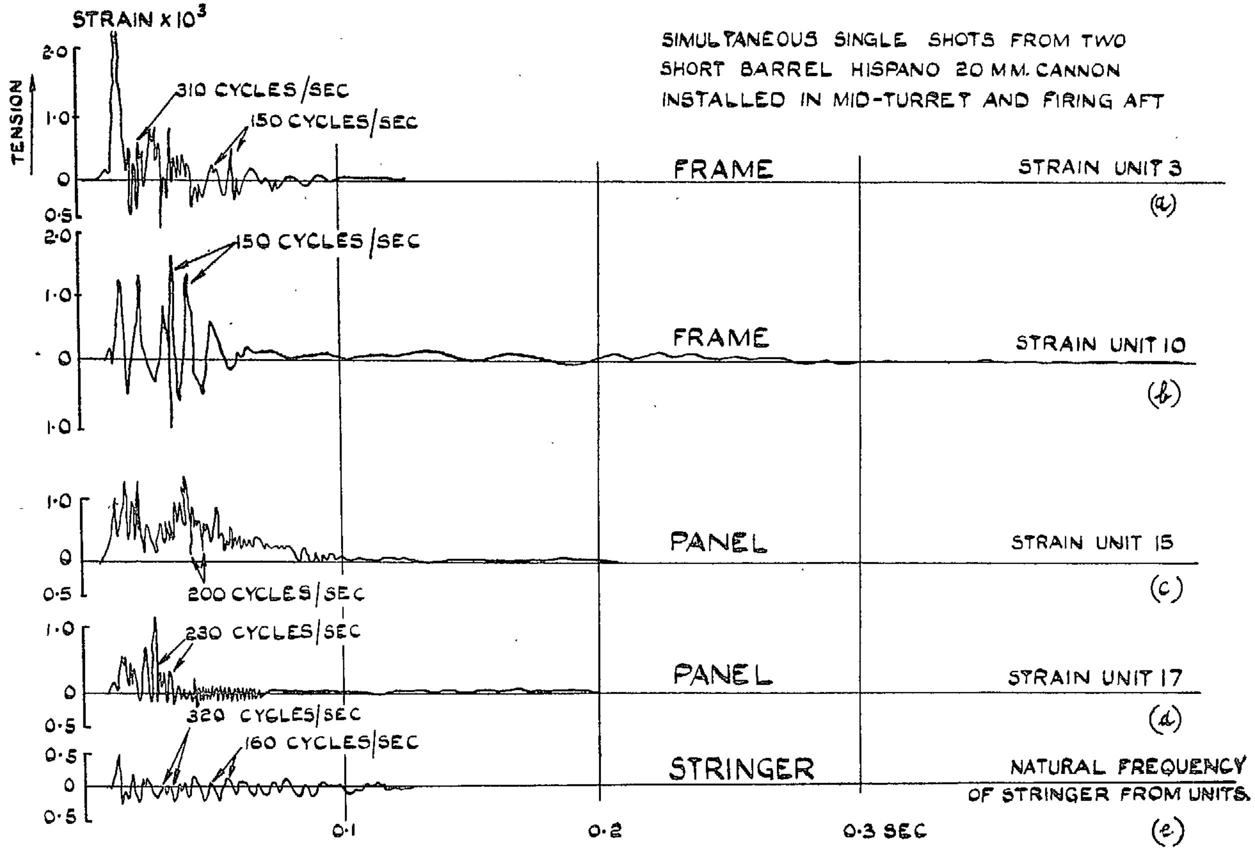


FIG. 64. Strain variations in *Lancaster* fuselage due to blast from Hispano 20 mm cannon.

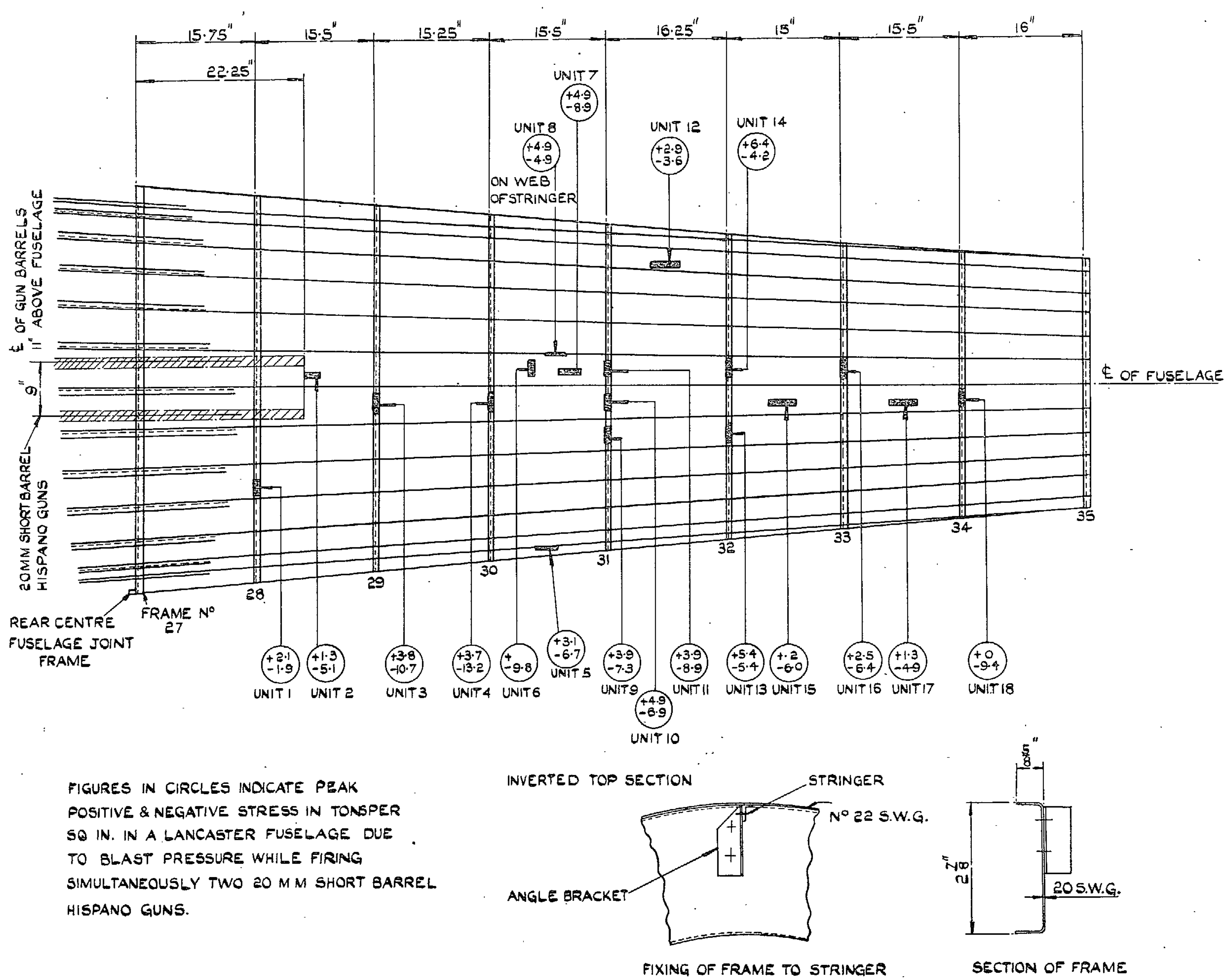


FIG. 65. Stresses due to blast pressure. *Lancaster* fuselage.

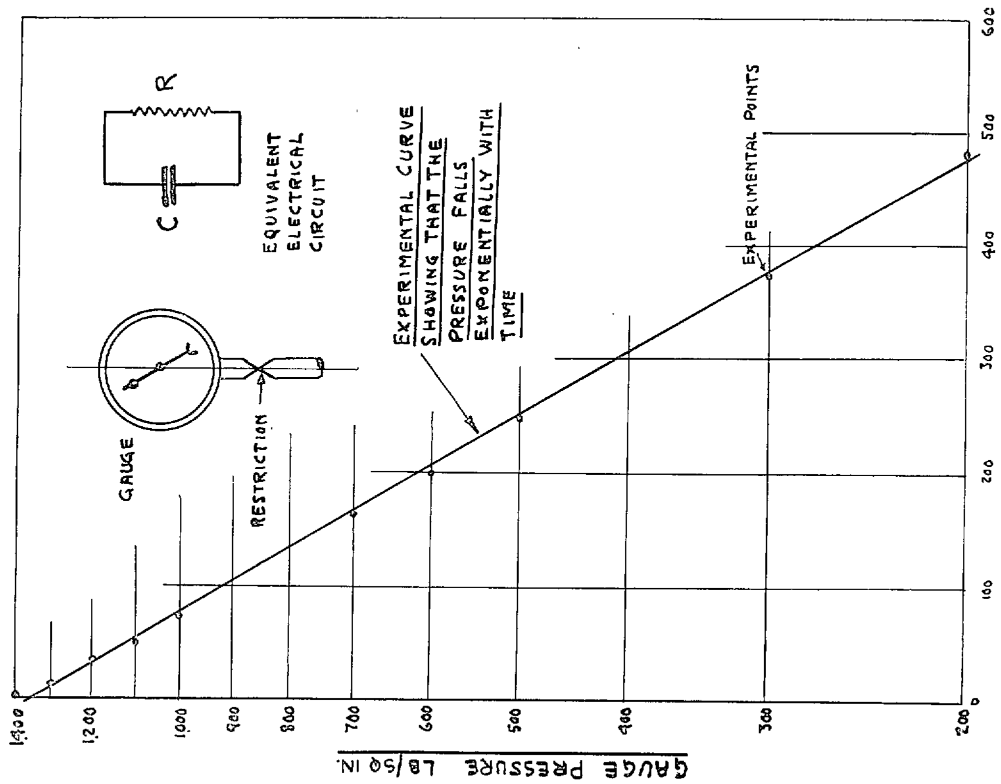


FIG. 66. Fall in pressure of oil gauge due to constant leak (Gauge number A.D.S. 48).

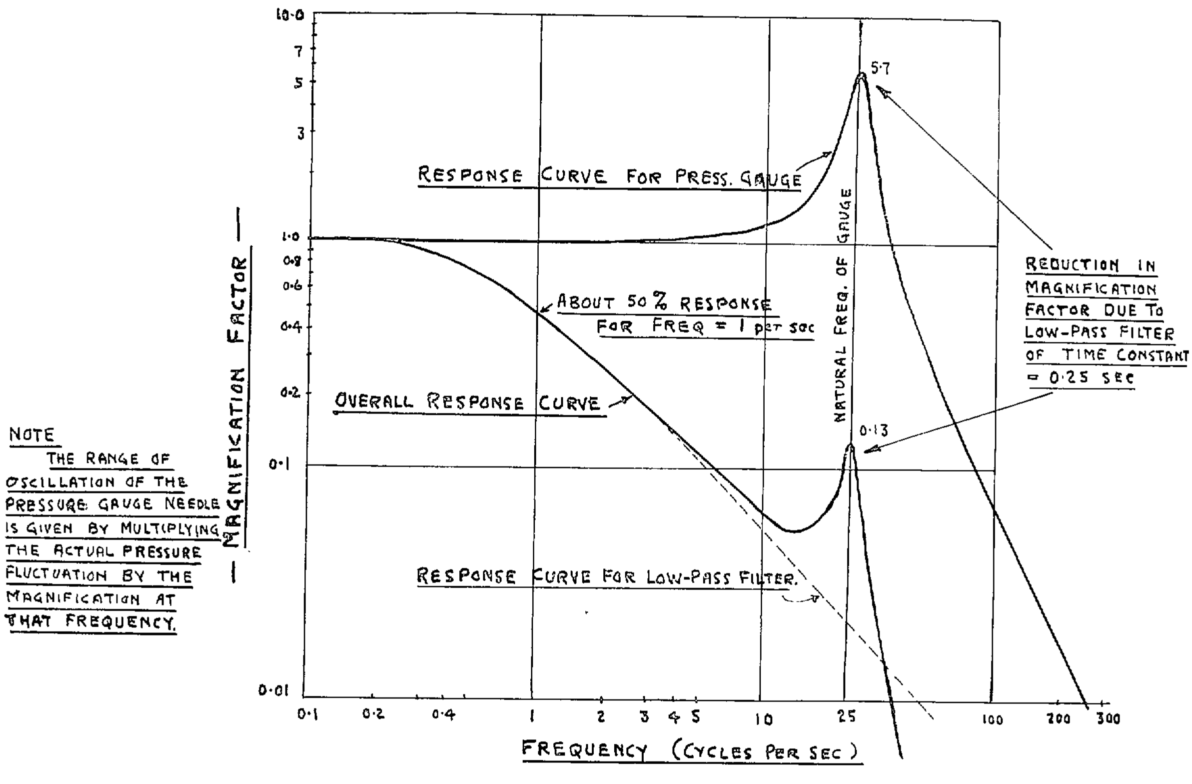


FIG. 67. Frequency response curves for oil gauge with and without low pass filter. (0 to 2,000 lb/sq in. oil gauge 2 in. diameter dial).

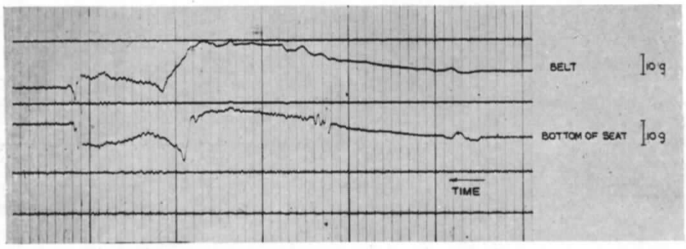


FIG. 68a. Acceleration on seat and belt on man during ejection on ground test rig.

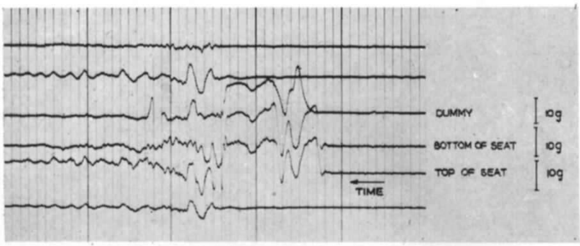


FIG. 68b. Acceleration on dummy and seat during ejection from aircraft on the ground. (Showing effect of flexibility of dummy).

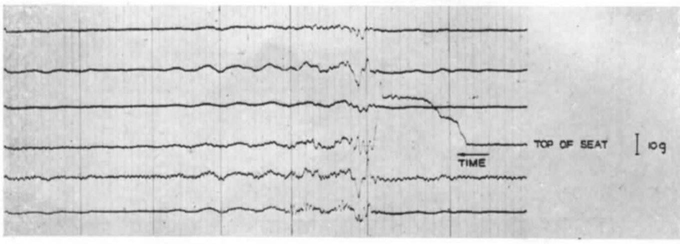


FIG. 68c. Acceleration on seat during ejection in flight.

Acceleration measurements during seat ejection.

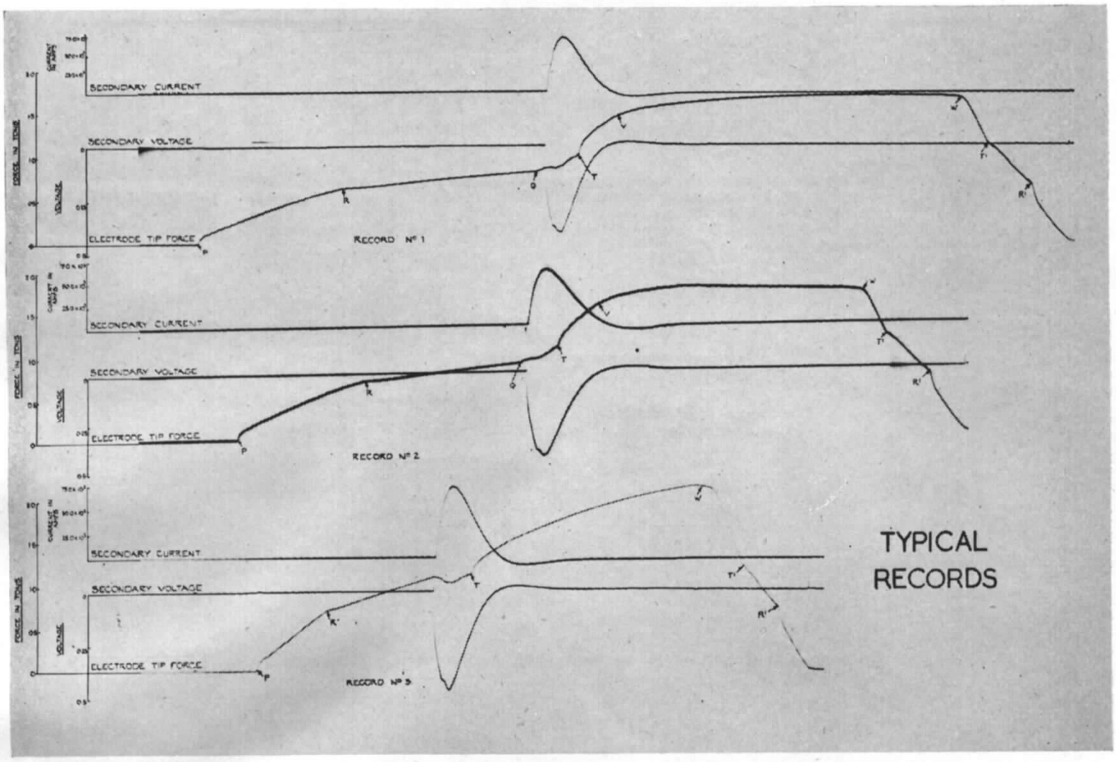
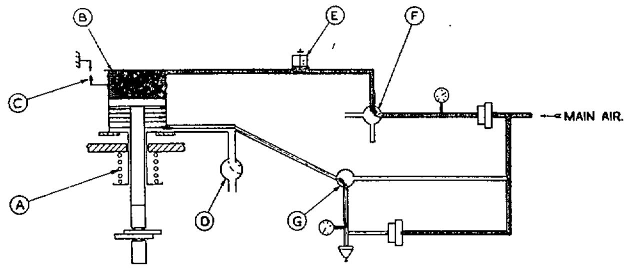
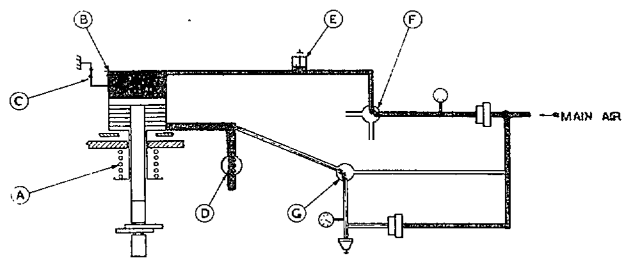


FIG. 69. Characteristics of light alloy spot welding machines. Typical records.

AIR TO TOP OF CYLINDER (80 LB/□") & CONTROLLED AIR (SAY 20 LB/□") TO BOTTOM OF CYLINDER. WHEN UPWARD FORCE ON CYLINDER (= DOWNWARD FORCE ON PISTON) EXCEEDS DOWNWARD FORCE OF PREVIOUSLY COMPRESSED SPRING Ⓐ CYLINDER Ⓑ STARTS TO RISE MAKING CONTACTS Ⓒ MAIN WELDING CURRENT FLOWS THROUGH ELECTRODES & VALVE Ⓓ OPERATES.



THE OPENING OF VALVE Ⓓ EXHAUSTS AIR FROM THE UNDERSIDE OF THE PISTON THUS APPLYING A SUDDEN INCREASE IN PRESSURE TO THE SHEET BEING WELDED. i.e. A FORCE IS APPLIED. AFTER VALVE Ⓓ HAS OPENED THE AIR PRESSURE STILL INCREASES ON THE TOP SIDE OF THE PISTON UNTIL IT REACHES A PREDETERMINED VALUE WHEN PRESSURE SWITCH Ⓔ CLOSES SO OPERATING VALVES Ⓓ Ⓕ & Ⓖ



AIR IS FED TO THE BOTTOM OF THE PISTON THUS RAISING THE ELECTRODE FROM THE COMPLETED WELD

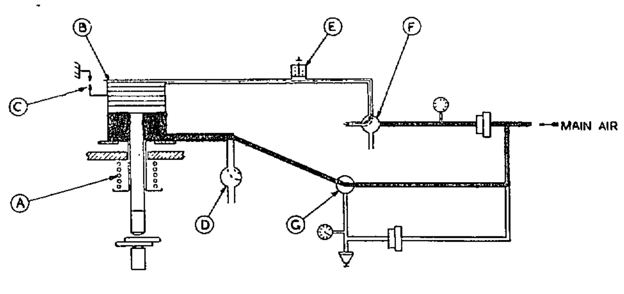


FIG. 70. Diagram showing operation of spot welding machine sequence of pneumatic cycle.

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