PATENT SPECIFICATION

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PROVISIONAL SPECIFICATION

Improvements in Means for Detecting, Observing, Measuring or Indicating Minute Movements

I, Edmund Ramsay Wigan, of 2, Brandram Road, Lee, London, S.E.13, a British Subject, do hereby declare the nature of this invention to be as follows:—

The essential elements of this invention are a relatively pliant member carrying suitably shaped gauging surfaces and means of setting this member into a steady or controlled state of vibration. Suitable adjusting means are provided so that these gauging surfaces may be brought into mechanical contact with the surface of any solid body with a view to determining the position in space of the latter or its state of motion. By suitably closing the frequency at which the vibrating member is driven, and by properly proportioning the parts of the apparatus, an unstable state of vibration is set up at the moment that contact is established between the gauging surface and the surface towards which it is approached. The behaviour of the apparatus is such that a very small and fleeting force of contact between these surfaces results in an increased force of contact when the surfaces approach each other again in the next cycle of vibration.

The resulting sudden increase in the force of contact serves to indicate that contact has been established. For example it causes an audible chattering sound which is readily observed; alternatively the change in the mode of vibration can be arranged to operate indicating means.

It will be appreciated therefore that this invention provides means of indicating in a simple, sensitive and accurate manner a very slight force of contact between two surfaces.

In an application of the above principle to a linear dimension gauge, the pliant member, mounted on a suitable supporting carriage together with associated means for maintaining and controlling the vibration of the member, corresponds, as a unit, with the usual "feeler" element of the gauge. The pliant member is controlled and maintained in vibration by, for instance, an electromagnetic drive.

The gauging surface or surfaces are approached to the object being gauged by a combination of coarse and fine adjustments. Contact between the gauge and the object is indicated by the phenomenon described above.

The fine adjustment is carried out, in one form of the gauge, by varying the current flowing in the electromagnetic system. The apparatus can be calibrated so that this current, the magnitude of which can be read from a suitable indicator, becomes a measure of the linear distance through which the gauging surfaces have been caused to move relative to the supporting carriage, that is, a measure of the fine adjustment.

In the special case referred to above the gauging member is caused to vibrate, but the invention may also be applied in cases where the surface under observation is vibrating and the gauging member is adjustable but not vibrated, or is adjustable and caused to vibrate. The various parts and the driving frequencies being so chosen that an unstable state of vibration is set up at the moment than contact is established between the gauging and the gauged surfaces. For example this invention may be applied to apparatus designed to indicate a maximum or minimum value of some physical quantity; the needle of a volt meter, for instance, may constitute the vibrating member, which at some chosen point on the scale is set into violent vibration by touching an adjustable stop; the energy thus released may be employed to operate indicating means.

Dated the 28th day of June, 1936.

E. RAMSAY WIGAN.

COMPLETE SPECIFICATION

Improvements in Means for Detecting, Observing, Measuring, Indicating, Recording or Utilizing Minute Movements

I, Edmund Ramsay Wigan, of 2, Brandram Road, Lee, London, S.E.13, a British Subject, do hereby declare the nature of this invention and in what manner the same is to be performed, to be particularly described and ascertained in and by the following statement:—

This invention relates to means for detecting, observing, measuring, indicating or recording minute movements or displacements and for utilizing such minute displacements for any purpose for which they may be suitable, and it has for its object improvements in such means incorporating the application thereto of a new technique, as will be described hereafter

According to my invention, I provide apparatus for detecting, observing, measuring, indicating, recording or utilizing minute changes of position of a solid body, an essential feature of which is of the nature of a linear dimension gauge or like device, consisting of (1) a gauge carriage which is movable with respect to a supporting bed and (2) a contact-indicating device, comprising a "feeler gauge surface" (or surfaces) carried upon a flexible resilient member or "vibrator" maintained by any suitable means in a state of vibration, the amplitude of which is normally steady or controlled, said apparatus being characterised in that the said flexible resilient member is so proportioned and mounted upon the said gauge carriage that the frequency of one of its modes of natural or resonant vibration is near to (above or below) the frequency of the forces maintaining the said member in vibration, the difference between these two frequencies being assigned such a value that when a "contact gauge surface" carried by the body the displacement of which is to be detected, observed, measured, indicated, recorded or utilized, comes in close proximity to the "feeler gauge surface" (or surfaces) so as to touch it with a certain very small force of impact, there is set up a particularly distinctive mode of intermittent contact between the "contact gauge surface" on the body and the "feeler gauge surface" on the flexible member, so that the said flexible resilient member breaks into a new vigorous mode of vibration, hereafter referred to as the "vigorous vibration", which is characterised in this, that this new mode of vibration does not return to the steady or controlled mode of vibration when the contact gauge surface is brought back into the position it occupied when the initial impact occurred, and even when it is withdrawn slightly further away.

The contact gauge surface instead of being carried by the solid body the displacement of which is to be detected, observed, measured, indicated, recorded or utilised, may be on a separate member adapted to be displaced directly or indirectly, by the said body.

The position of the contact and feeler gauge surfaces may be interchanged, the resilient vibrating member carrying the feeler gauge surface being mounted on the solid body the displacement of which initiates the phenomenon referred to, and the contact gauge surface being carried by a suitable fixed member.

It has been found that the substitution of the unstable distinctive mode of vigorous vibration of the flexible resilient member for the steady or controlled state of vibration constitutes a far more precise indication of the close proximity of the feeler and contact gauge surfaces than any method of mechanical or electrical contact hitherto provided can give, so that, by this method, displacements of the order of one ten millionth of an inch can be easily detected, observed, measured, indicated, recorded or made use of, as will be more fully shown hereafter, such detection, observation, measurement, indication, recording or utilization being hereafter referred to as a "gauging operation" for the sake of briefness.

The behaviour of the apparatus is such that a very small and transitory force of contact between the feeler and the contact gauge surfaces results in an increased force of contact when the surfaces approach each other again in the next (or in a subsequent) cycle of vibration.

The resulting rapid increase in the force of contact serves to define the body's position at the moment that the initial contact is established. For example it may cause an audible chattering sound which is readily observed or it may cause the flicker of a pointer when coming in contact with a stop; alternatively the change in the mode of vibration can be arranged to operate visual indicating, or recording means, or to bring about any desired mechanical or other operation.

It will be appreciated therefore that this invention provides means for indicating in a simple, sensitive and accurate manner that a very slight force of contact has developed between the two gauging surfaces.

In an application of the above principle to a linear dimension gauge, the flexible resilient member, mounted on a suitable supporting carriage together with associated means for maintaining and controlling the vibration of the said member, corresponds, as a unit, with the usual "feeler" element of the gauge. The flexible resilient member may be controlled and maintained in vibration by any known suitable device, such as an electromagnetic drive. The feeler gauge surface (or surfaces) are brought near to the contact gauge surface (or surfaces) on the body being gauged by a combination of coarse and fine adjustments. Vibratory contact between the feeler gauge surface and the contact gauge surface on the body being gauged is indicated by the phenomenon described above.

In one form of gauge the fine adjustment is made either by altering the amplitude of the vibration by varying the alternating current flowing in the electro-magnetic system, or by displacing the mean position of the vibrator by superposing an adjustable direct current on this alternating current. The apparatus can be calibrated so that either (or both) these currents, the magnitude of which can be read from a suitable indicator, becomes (or become) a measure of the linear distance through which the feeler gauging surface or surfaces have been caused to move relative to the supporting carriage, that is, becomes (or become) a measure of the fine adjustment.

In the various cases referred to herein it will be assumed for the sake of illustration that the feeler gauging surface is carried by the flexible resilient member which is caused to vibrate, but it will be understood that the invention may also be applied in certain cases where the body under observation is vibrating and the feeler gauging member is adjustable and either is not vibrated (in which case the body under observation enters into vigorous vibration when vibratory contact takes place), or is also caused to vibrate, the various parts being so designed and the driving frequencies being so chosen that a vigorous state of vibration is set up at the moment that vibratory contact is established between the two gauging surfaces For example this invention may be applied to apparatus designed to indicate a maximum or minimum value of some physical quantity: the pointer of a voltmeter for instance, may constitute the vibrating member, which, at some chosen point on the scale, is set into violent vibration by touching an adjustable stop; the energy thus released may be employed to operate indicating or recording means. If the stop is set at a certain minimum or maximum reading, it being required to give a warning whenever the pointer comes in contact with the stop, the device may be used as a minimum or maximum voltage indicator.

It will therefore be seen that in every case, the invention involves the combination of two features, one of which is the material embodiment of what may be aptly referred to as the "vigorous vibration" phenomenon and the other of which is constituted by the means adapted for obtaining and for controlling very small displacements of the "feeler" member.

Operation.

The setting in of the particularly distinctive mode of vigorous vibration is obtained by causing a vibrating element, which carries a feeler gauge surface, to be in a steady state of vibration at a frequency near to and either above or below, but preferably above its natural frequency (or one of its other modes) of vibration. For example the frequency of the driving force may be below and near that of the higher modes of vibration, but above the fundamental mode of vibration. Only under exceptional circumstances does the driving frequency have to be very precisely chosen. For various subsidiary reasons, it should, however, be as constant as possible.

As already stated, the fine adjustment of the "feeler gauge surface" of the linear gauge is preferably obtained by using a relatively stiff member or system of members for the vibrator and deflecting this by the application of forces, preferably derived from an electromagnetic arrangement. It is found that, by superposing in the same magnetic system the fluxes due to both the deflecting current (D.C.) and the main oscillatory driving current (A.C.) the flux due to the former current produces no serious hysteresis effects; moreover the deflection of the mean position of the vibrating feeler element becomes practically a linear function of the D.C. A current-measuring instrument can therefore be arranged to indicate the deflection by indicating this current.

Means of controlling these small movements of the feeler gauge surfaces by an automatic process (hereafter referred to as "auto-control") become important when the invention has any but the very simplest form, namely, a simple distance gauge. The most fruitful field of application of the invention appears to be concerned with such auto-controlling means. As will be seen from the charts given hereafter, all but the primary applications are concerned with auto-controlling devices.

Controlling Means.

The simplest form of control is a hand-control: by slowly increasing the A.C. or D.C. electric current flowing in the electromagnetic system of the vibrating element, the feeler gauge surface is brought near to the contact gauge surface on the body the displacement of which is to be ascertained until the sudden setting in of the vigorous vibration, indicated by a violent rattling of the gauge device, indicates that " vibratory contact " has been established. The value of the current read on the current-measuring instrument is a measure of the distance the gauge has moved prior to contact. The reading can be checked by reducing the current to the point at which the vigorous vibration is extinguished and then bringing again the feeler gauge surface near to the contact gauge surface.

Auto Control.

All the methods of auto-control so far devised carry out this procedure automatically. In certain arrangements a relay is arranged to be energised (by one of several possible schemes) when vigorous vibration is set up. The operation of the relay tends to extinguish the vigorous vibration by the means described hereafter, for example by reducing the A.C. fed to the vibrator. When the vigorous vibration is extinguished the relay is automatically deenergised and the feeler gauge surface (or surfaces) again approaches the contact gauge surface. The operation may be adapted to operate a recorder, so as to give an automatic record of the position of the contact gauge surface; this arrangement is referred hereafter as " auto-recording ".

In order to prevent " hunting " of such an arrangement, the return of the vibrator is made with as little shock as possible, for example, the current controlling the vibration is derived from a condenser-resistance network which only permits slow movements of the mean position of the vibrator. In another arrangement the use of a relay is avoided by substituting for it a network containing a resistance combined with a condenser, the potential across which is the source of the controlling current and is directly controlled in magnitude by the amplitude of vibration of the vibrator.

Types of Auto-Control.

The amount of control exerted by the relay depends upon the function of the gauge device. If it is to keep a continuous record of a changing length the vigorous vibration is completely extinguished (as, for instance, by reducing the deflecting force to zero) immediately after this vigorous vibration is initiated.

If, however, the gauge is designed to give warning of very small changes in the length of, for example, a thermostat element, the vigorous vibration is not immediately extinguished when contact has been established, but instead it is brought to the point of incipient extinction by the withdrawal of the contact or feeler gauge surface through a small distance. With things adjusted in this manner, a very small further withdrawal of the gauge surface carried by the gauged body (i.e. as would be caused by a fall in temperature of a thermostat element) results in the complete extinction of the vigorous vibration, the re-opening of the relay, and the return of the gauge device to the position it occupied at the beginning of the cycle of events.

In this form the gauge device gives a warning (by the operation of the relay) directly the gauge surface carried by the gauged body reaches a certain point, namely, that at which vibratory contact is established, or goes beyond it. The warning is continued until this surface has been withdrawn sufficiently to extinguish the vigorous vibration. It will be clear therefore, that a gauge in this form can be used as a maximum (or minimum) indicator or controlling device, as has been already explained.

It should be noticed that the gauge device is capable of acting as a maximum (or minimum) indicator without the addition of subsidiary control by a relay. Without this control, however, there is a large difference between the position (or length) of the gauged object at the moment the vigorous vibration is initiated by vibratory contact with the gauge, and the portion (or length) to which it has to return before this vigorous vibration extinguishes itself.

This discrepancy between the lengths required to start and to stop the vigorous vibration is a serious fault. The operation of the relay-controlled circuit is designed to reduce this discrepancy.

For example, in a gauge device which develops a considerable amplitude of vigorous vibration, the length-discrepancy referred to may be 50 to 100×10^{-6} ins. This can be reduced to about 1×10^{-6} ins. by the auto-control arrangement. The great value of this arrangement is that the gauge device can be designed to develop violent vigorous vibration (which is an advantage in operating relay controls etc.) while still remaining sensitive to very small reductions in the gauged distance.

Compensation for Variation of Supply Voltage.

In all that has been said so far a tacit assumption has been made, namely, that the forces driving the vibrating member of the gauge device are either constant or variable, but that they are all known.

In many forms of the gauge device it is desirable to reduce to a minimum the influence of these forces upon the gauging operation and to produce all the required fine adjustment or "gauging" movements of the vibrator by means of a D.C. source. (The primary reason for this is that the discrepancy referred to above, due to the vigorous vibration, becomes greater as the alternating forces increase: for many purposes this increase appears to be unmanageable). It will be appreciated that the distance between the feeler gauge surface and the contact gauge surface the displacement of which is being observed, is a function of the A.C. driving forces as well as the D.C. deflecting forces. As the value of the D.C. is the more readily controlled and indicated, it is the A.C. which is preferably kept constant while the D.C. measuring instrument is calibrated to read "distance".

When the apparatus is supplied from the public supply, a variation of at least $\pm 5\%$ is to be expected in A.C. voltage. (Say $\pm 5 \times 10^{-6}$ ins. uncertainty in the gauged length unless an A.C. measuring instrument is provided so that the driving current can be set to the proper value). This uncertainty is serious if ignored, and if provided for by separate control, the operation of the gauge ceases to be entirely automatic.

Two ways of avoiding this fault have been devised.

METHODS OF COMPENSATION.

In the first the vibrator is driven by an unpolarised magnet system. This has the effect of:

(1) causing the vibrating resilient member to vibrate with a frequency which is twice that of the driving forces;

(2) shifting the mean position of the vibrator towards the magnet system.

As the amplitude of (1) is of the same order as the value of (2), the nett effect is that changes in the driving current have little or no effect upon the position in space of the extreme point reached by the feeler gauge surface when the vibrator is receding from the driving magnet. Other advantages of an unpolarised winding are simplicity and the removal of one source of possible error, namely, the ageing of the magnet causing a diminution of the total flux.

In the second method of compensation, the driving magnetic circuit is polarised by a magnet and is supplied with both A.C. and D.C., both derived from the same source, the latter by rectification. The direction of the D.C. is arranged so as to shift the mean position of the vibrator away from the surface gauged, as the A.C. voltage rises. Owing to the non-linear characteristic of the rectifier this arrangement is not perfect but can be adjusted to reduce very considerably the influence of variations of the mains voltage upon the true reading of the gauge device. The advantage of this arrangement is that the driving system may be mounted on whichever side of the vibrator is most convenient mechanically. Moreover, owing to the permanent magnet, this scheme permits further control of the vibrator by superposition of a second, controlled, and indicated, direct current which can be used to effect the gauging operation, as described herebefore.

Further advantages of using a polarised winding are that both attractive and repulsive forces, as may be desired, may be exerted on the vibrator by suitably directed currents, and that the response of the vibrator to such currents and to alternating currents tends to be closely linear.

CIRCUITS CONTROLLING THE RELAY.

It has now been shown that the gauge device can be made insensitive to supply variations and that it can be arranged to be auto-recording, or auto-controlling of subsidiary apparatus. All this depends upon the vigorous vibration being able to operate a relay and so to bring the controlling effects into action. There are two principal ways of operating the relay:

(1) by a circuit completed through the feeler and the contact gauge surfaces:

(2) by the vigorous vibration causing a subsidiary jar-sensitive or "chatter" contact to break the circuit.

Clearly the method (1) cannot be used for measurements of the very highest precision because the passage of the current causes local heating which leads to unknown and probably irregular local expansions of the gauge surfaces (of the order 10^{-5} ins.). It is, however, the more direct method of control. For example, a relay can be de-energised by the discharge, by way of the two gauge surfaces, of a very large condenser connected across the relay: being large, the condenser cannot immediately recharge and so the relay remains open so long as vibratory contact is maintained. In an alternative arrangement, a quick acting relay can be operated through the gauging surfaces so as to operate with the frequency of the vigorous vibration. This relay can cause another to operate steadily (by the method (2) below) so long as the vigorous vibration lasts, this second relay being the main control-relay.

Method (2) is the best for the more precise gauges: it has the disadvantage, however, that it is suitable only for the more massive vibrating systems, and these again are suitable only for observing the movement of relatively massive surfaces. The " chatter " contact may be mounted on the vibrating element of the gauge device, chattering being induced directly the vigorous vibrations begin; or the " chatter " contact can be mounted on the member carrying the contact gauge surface under observation, if this member is of suitable form and is sufficiently resilient to transfer the jarring of the vigorous vibration to the chatter-contact. The chatter-contact is in parallel with the relay (which it normally short-circuits). The relay is fed with D.C. through a choke and a resistance (from a rectifier if convenient). The chattering of the contact forces the current normally passing through the contact to pass through the relay. This effect is emphasised by the choke. The relay is thus forced to operate quickly in spite of its own inductance. The relay remains operated so long as the contact chatters. The operation is assisted by a small spark-quenching circuit connected across the chattering contacts.

Applications of Gauge.

The field of application of the new device according to the present invention is obvious in certain directions: for example, it may be used:

(1) as the control element of a thermostat regulator; this is obvious in view of what has been stated above the thermostat expansion element carries the contact gauge surface and another member, adjustable in position, carries the feeler surface; expansion of the thermostat element causes vibratory contact and this actuates a relay which controls the heating and at the same time brings the vigorous vibration to the point of incipient extinction. Contraction of the thermostat element then results in the complete extinction of the vigorous vibration, the re-opening of the relay, the return of the feeler surface to its initial position and the resumption of the heating. The relay can be made also to operate a recorder.

(2) as the " feeler " element of a linear dimension gauge of any known kind; this feeler element has already been described in detail. It can be combined with a recording device of a suitable type.

(3) as a micro-barograph using a single, temperature-compensated capsule carrying the gauge surface, in combination with an auto-controlled feeler surface caused to approach the gauge surface at intervals, the position of the feeler surface when vibratory contact takes place being recorded in any suitable known manner by apparatus under the control of the device employed to make the gauging operation and giving an indication of the barometric pressure in terms of the movements of the capsule.

(4) as a recording extensometer for small test pieces or samples, brackets being clamped at the two ends of the test piece under observation, one carrying the gauge surface, the other the feeler surface, and arranging the apparatus to give as in (3) above, a record of the change of length of the test piece or sample under test.

Pointer Instruments.

When it is adapted to determine the position of a pointer on a scale, however, the gauge makes possible a number of special developments:

(5) the position of the pointer of an electrically controlled pointer instrument can be determined with an error of about 10^{-4} ins.;

(6) as a development from (5), the movement of the pointer of a primary instrument may be duplicated and magnified by a secondary instrument, so that a robust, quick-acting, insensitive measuring instrument can be used (as the secondary instrument) to measure with accuracy quantities, e.g. currents, which cause a deflection of a few thousandths of an inch of the pointer of the primary instrument. For instance, a quick-acting, sensitive, thermo-electric pyrometer can be designed on these lines;

(7) any physical quantity which can be measured electrically using a " bridge " method can be kept under control by providing the current measuring instrument which indicates the " balance " with a gauge device as described above, for instance illumination, resistance, inductance, velocity, may be measured in this manner;

(8) any pointer instruments, whether electrical or not, can be provided by its means with maximum or minimum deflection indicators;

(9) particularly designed electrical pointer instruments can be developed which avoid the complication of pivots and coiled springs and have only minute deflections. These deflections are, however, magnified and if necessary recorded on the lines of (7) and (8) above.

The setting-in of the particularly distinctive vigorous vibration may be observed either by ear, directly or by means of a microphone, or by eye, for example by the flicker of the pointer of a measuring instrument, as already mentioned or by the change of the shape of the oscillation envelope, a method which will be described hereafter.

The apparatus embodying the invention may easily be adapted to any particular ordinary laboratory technique; for example, it may comprise an electric circuit completed by means of a photo-electric cell or device of a similar nature, influenced by a radiant beam which is under the control of the mode of vibration of the vibrator.

The appended charts show at a glance the extent of the range of application of the invention, by indicating broadly the various modifications which may be effected in its methods of application (Chart 1) and the various effects produced by the operation of the auto-controlling-circuit (Chart II). It will be understood that I do not claim as my invention the numerous manners referred to of observing the setting in of the vigorous vibration phenomenon. These methods of observation are well known and belong to usual laboratory technique.

A few apparatus, selected among the most important of the applications of which the invention is capable, will be now described as examples which are by no means limitative in any respect.

Referring to the drawings left herewith, which illustrate, on sheets 1 to 4, for the sake of illustration only, apparatus embodying the present invention, and, on sheet 5, the Charts referred to above:—

Fig. 1 represents diagrammatically a vibrator for a simple form of gauge, according to the invention;

Figs. 2, 3*a*, 3*b*, 4*a*, 4*b*, 4*c*, 4*d*, 5 and 6, are diagrams of electric circuits used in connection with the gauge shown in Fig. 1;

Figs. 7, 8*a* and 8*b* represent diagrammatically constructional parts of apparatus embodying the invention;

Fig. 9 is a diagram of an electric circuit illustrating an application of the invention for ascertaining with extreme accuracy the position of a pointer on a scale.

In Fig. 1 the primary elements of a simple form of the gauge are illustrated. In this form the vibrator element 4 is maintained in oscillation by an electro-magnetic system 3. The vibrator 4, which is mounted on a support 5, on a base 7, carries the "feeler gauge surface" 1, and a mass 2 adjustable in magnitude and in position, the said mass being so chosen that one of the natural periods of vibration of the vibrating system 1—2—4 together with the mass 6 is near to the fundamental frequency of the forces developed on the vibrator 4 by the system 3, or to one of the overtones of this frequency. When so adjusted, as it has been explained above, the mode of vibration of the vibrator element changes to vigorous vibration as soon as the surface 1 touches a solid body with a certain minimum force. (This minimum force becomes smaller as the frequency of the driving forces approaches more closely the frequency to which the vibrator is adjusted to resonate). A jar-senstive electrical contact is shown at 6; this consists of a small, light, spring 6^1 carrying a mass at the free end which it holds against a contact 6^{11} carried by the vibrator 4. This arrangement can be adjusted in such a way that it is unaffected by the steady vibratory motion of the vibrator 4 but so that it momentarily breaks the contact between the mass 6 and the contact 6^{11} when the mode of vibration of the vibrator 4 is changed owing to the "vibratory contact" of the feeler gauge surface 1 with the object gauged.

Both the support for the spring 6^1 and also the contact 6^{11} against which the mass bears, are mounted on the vibrator, suitable arrangements being made to carry an electric current to and from the contact surfaces.

The jar-sensitive contact is necessary only when the gauge is to be used in conjunction with certain types of subsidiary controlling apparatus; for the more simple applications of the gauge it is sufficient to provide other means of observing the jarring of the vibrator: for example, a microphone "button" *p* may be fixed to the vibrator, preferably near to or at the support 5.

The jar-sensitive contact 6 is preferably mounted in the manner shown in the figure, that is, so that the rebound of the feeler gauge surface 1 from the object gauged tends to withdraw the vibrator 4 away from the mass, which is delayed by its inertia.

If the feeler gauge surface 1 Fig. 1 is reversed and is pointed towards the base 7, it is possible, by suitably choosing the material and the dimensions of the members, 1, 4, 5 and 7, in the known manner, to arrange that changes in the mean temperature of the parts of the gauge have no effect upon the distance between the surface 1 and the base 7.

In Fig. 2, a circuit is shown which provides for the energisation of a relay 8 by the momentary opening of the jar-sensitive contact 6 ("break" control). The relay is operated by means of a source of current such as the battery 11 or the single-wave rectifier 13 (it is however preferable not to employ alternating current if very rapid response of the relay is desired). A resistance 10 is provided to limit the intensity of the current when the jar-sensitive contact 6 is closed. A choke coil 9 may be put in the circuit; it is of assistance in two ways: when a rectifier 13 is used it helps to maintain the alternating P.D. across the rectifier when the jar-sensitive contact 6 is closed, and thus reduces the delay in the operation of the relay when this contact opens. Again, when either supply arrangement is used, the electrical inertia of the choke coil 9 assists the operation of the relay 8, since it tends to force the current flowing through the jar-sensitive contact 6 to flow through the relay 8 without any alteration in its magnitude; this assists the quickness of response of the relay. A spark-quenching circuit 12 assists the operation of the circuit and tends to protect from pitting the contacting surfaces of the jar-sensitive contact 6.

In Fig. 3*a*, a circuit is shown which illustrates a method for the de-energisation of the relay 8 by the intermittent closing of the circuit at a pair of contacts 14 which represent the pair of gauging surfaces (" make " control). The relay is operated by power sources 11 or 13 as in Fig. 2, except that the choke coil 9 is omitted. A large condenser 15 is substituted for the spark-quenching circuit, this condenser being discharged by completing the circuit at contacts 14. The degree of discharge depends upon the duration of the contact and the resistance of the discharge circuit. It is found that, with condensers of 2000 microfarads charged to 4—6 volts, safety resistances of 50 ohms or more can be inserted at *r* without seriously interfering with the operation of the circuit. Such resistances reduce the likelihood of the contacts at 14 becoming welded together. By suitable choice of the resistance 16 the relay 8 can be made to remain with its contacts " open " for a considerable period of time, say up to 1 second, if in this interval of time no new closing of the circuit has occurred at 14. In this way a chattering, i.e. intermittent, contact at 14 results in the continued partial de-energisation of the relay 8 and, consequently, in the contacts of the relay being maintained in the same position. The cessation of the contacts at 14 results, after a delay, in the relay-contacts moving back into their alternative position. This delay is a disadvantage in certain cases, and it may be avoided by using the circuit shown in Fig. 3*b*. In this circuit the pair of contacts 14 represent the feeler gauge surface 1 and the contact gauge surface on the body gauged, which make intermittent contact when the vigorous vibration is initiated, thus operating the relay 18 through the battery circuit 17, thereby causing the contact 19 of the relay 18 to " chatter ". This energises the relay 8 as explained in connection with Fig. 2.

Fig. 4*a* shows the simplest method of controlling the movement of the vibrator of a gauge of the type shown in Fig. 1. In this figure, the winding *g* is the wind- of the electromagnetic driving system 3 of Fig. 1.

A resistance *a*, and a current measuring instrument *m* are shown in series with the winding *g*. The former is preferably invariable in order to keep uniform the behaviour of the gauge when in the vigorous vibration state; the adjustment of the alternating current is made by means of the potentiometer resistance *b*. The current-measuring instrument *m* should be quick acting, for example, of the rectifier-fed type. The resistance *b* is adjusted by hand until the amplitude of vibration of the gauge is sufficient to cause contact between the feeler gauge surface 1 (Fig. 1 and the contact gauge surface of the object gauged. The sudden appearance of the vigorous vibration indicates that vibratory contact has been established. The reading of the instrument *m*, corresponding to the appearance of the vigorous vibration, is noted. Any relative displacement between the feeler gauge surface and the contact gauge surface of the gauged object can then be measured by repeating this process and noting the new reading of the instrument *m*. The difference in the readings is a measure of the displacement.

The three main drawbacks of this arrangement are:

(1) the changes in current must be made very gently so that the vibrator is not noticeably jarred;

(2) the accuracy of measurement varies from point to point on the scale of measurement, for when the current is large the gauge is most sensitive and reciprocally;

(3) as the accuracy attainable is not much better than 1% (owing to (1), above) the smallest distance measureable is comparable with the amplitude of vibration (which may be 600×10^{-6} ins.).

Practically all these deficiences can be made good by using the circuit shown in Fig. 4*b*. It will be noted that, in this circuit, the apparatus windings now carry D.C. as well as A.C., the intensity of the latter being constant while measurement is in progress. A blocking condenser *e* prevents leakage of D.C. through the A.C. current measuring instrument m^1. The D.C. is used to make the measuring operation by shifting the mean position of the vibrator towards the contact gauge surface of the body under observation. It is read on the current measuring instrument *m*. In practice if this instrument *m* has a uniform scale and the gauge windings are polarised, its readings are very closely proportional to the displacement of the axis of vibration of the vibrator 4 (Fig. 1). The resistance *c* is used to control the current in the instrument *m*. By using a very large condenser at *d*, sudden shocks are not transmitted to the vibrator element of the gauge; moreover, as the condenser and resistance network can be made to have a very large time constant the movement of the needle of the instrument *m* is very slow and its position can be judged very closely by eye when the vigorous vibration makes its appearance. Since the amplitude of vibration is practically unaltered by the superposition of the D.C. on the A.C., the precision of operation of the gauge is practically independent of the reading of the instrument *m*. Again, very small displacements can be measured with this arrangement (e.g. a displacement of 10^{-6} ins. can be measured with an accuracy of about 5 to 10% when the amplitude of vibration of the feeler gauge surface is $200—300 \times 10^{-6}$ ins.). By using a vibrator element of greater stiffness, measurements of still smaller displacements can be made.

It is found that the presence of the alternating flux due to the A.C. reduces the hysteresis effects naturally associated with the unidirectional but variable flux produced by the changes of D.C. during the gauging operation. The maximum value assumed by the D.C. may equal the maximum value of the A.C. without the hysteresis becoming sufficiently large to affect the calibration of the gauge. A choke coil 9^1 may be inserted in the D.C. circuit to reduce the intensity of the A.C. passing through the instrument *m*.

Owing to the extreme slowness with which the D.C. can be altered the arrangement of Fig. 4*b* can be made to give very high accuracy.

In order to obtain results more quickly, but with slightly less accuracy, the arrangement of Fig. 4*c* can be used. In this the gauging operation is entirely automatic and cyclic.

A suitable amplitude of vibration is obtained by setting the A.C. at a fixed value. The gauging operation is carried out by D.C. on the same principles as with the arrangement of circuits shown in Fig. 4*b*. The D.C. is controlled by the operation of a relay such as 8 in Figs. 2 or 3, which is itself under the control of the gauge. Thus the relay may be connected so that the contact 16 is opened at the moment vigorous vibration of the feeler gauge surface occurs. If, now the connections are such that the current from the battery causes the contact and feeler gauge surfaces to approach each other, the opening of the contact 16 results in the condenser 19 slowly discharging and in the contact and feeler gauge surfaces separating. The separation will continue so long as the vigorous vibration persists, but, as soon as the withdrawal is sufficient, the vigorous vibration vanishes, the relay contact closes again and the gauge surfaces again approach each other. Thus a cyclic operation is carried out; the maximum indication of the current-measuring instrument *m* is a measure of the distance through which the feeler gauge surface has been displaced by the D.C. An alternative circuit is possible in which the relay 8 short-circuits the condenser 19 (by means of the contact 17) at the moment vigorous vibration is initiated. This restores the current measuring instrument and the vibrator to their undeflected positions and the cycle of operations proceeds as above. Here also a choking coil 9 may be inserted in the D.C. circuit.

In Fig. 4*d*, instead of operating a relay, the jar-sensitive contact *k* is arranged to cause the large condenser 19 to charge up as soon as the contact *k* begins to chatter. In the figure, the source of P.D. by which the condenser 19 is charged is shown as a single wave rectifier. The appearance of a P.D. at the terminals of the condenser 19 causes a unidirectional current to flow through the D.C. measuring instrument *m* and the driving winding *g* of the gauge, and this causes the arrangement to function in a manner similar to that of the circuit shown in Fig. 4*c*. The object of this modified arrangement is to obtain a quicker response of the controlling current to the chattering of the contact *k*.

Fig. 5 represents a circuit which is adapted to be inserted between the exciting winding *g* of the gauge and the source of A.C., in order to make the scale of measurement, which is based on the reading of the D.C. measuring instruments of Figs. 4*b*, 4*c* and 4*d*, independent of small chance variations in the alternating current supplying the vibrator. The function of this circuit is to provide a biassing unidirectional current as closely as possible proportional to the alternating current which passes through the circuit. For many purposes the circuit of Fig. 5 does this with sufficient accuracy, but, when greater accuracy is essential, more complex circuits can be easily devised on the same principles. It will be seen that the rectifier 24 with resistance 21 and condenser 20 are connected in parallel with the source of A.C. The P.D. across the rectifier 24 will therefore vary in conformity with any change in the P.D. supplying the exciting winding g of the gauge. The rectified current produced by 24 is passed on to the winding g by a choke coil 28. The A.C. current measuring instrument 26 is isolated from the D.C. circuit by the condenser 22. Adjusting resistances 21, 23 and 27 make it possible to adjust the relative proportions of A.C. and D.C. supplied to g. The direction of the D.C. is arranged so that it withdraws the axis of vibration of the gauge away from the surface gauged. In a gauge employing this circuit it was found that $\pm$ 25% variation in the value of the A.C. potential at the terminals of the apparatus resulted in an error of $\pm 5 \times 10^{-7}$ ins. in the measurement scale. The amplitude of vibration of the feeler gauge surface was 200 to 300×10^{-6} ins.

As mentioned earlier the same effect can be obtained by employing a non-polarised winding at g, without the biassing circuit. Then if the gauge is assembled in the form shown in Fig. 1, the position in space of the upper edge of the envelope of the vibration of the surface 1, as viewed with the aid of an oscilloscope, for example, can be made practically independent of the value of the A.C. flowing in the windings 3. If there is a slight fall of the envelope edge when the A.C. is increased, the mass 2 (Fig. 1) is readjusted to bring the vibrator more closely into resonance with the driving current, and reciprocally.

When the gauge is employed for other than pure distance-measurement various subsidiary circuits are useful. For example, if the circuit of Fig. 4c is modified by the omission of the resistance r and of the contact 17 it may be used to convert the gauge into a maximum or minimum indicator or controller, the current from the source 18 of D.C. being adjusted so that the closure of the contact 16 does not completely extinguish the vigorous vibration the extinction being completed by the withdrawal of the contact gauge surface of the body gauged.

If it is found desirable to control the circuit of Fig. 4a by automatic means, it becomes necessary to alter the alternating current in a gradual manner. This can be done by the artifice illustrated in Fig. 6. A "bridge" rectifier is inserted in one of the A.C. leads, having a large condenser 30, shunted by a resistance 29 in series with a contact 28 which, for example, may be one of the contacts controlled by the relay 8. This contact is normally closed so that the bridge offers a relatively low impedance to the A.C. If the contact 28 is opened, however, (as a result, for instance of the setting in of the vigorous vibration and the operation of a relay), the condenser 30 charges up slowly and opposes the A.C. This has the effect of reducing the A.C. fed to the vibrator and therefore causes the extinction of the vigorous vibration. On the closing of the contact 28 the condenser discharges slowly through the resistance 29 and the cycle repeats itself. A condenser of 2000—4000 microfarads is suitable with a bridge having an effective resistance of about 1000 ohms.

The two methods of extinguishing the vigorous vibration, namely, the shifting of the mean portion of the vibrator by a D.C. and the reduction of the amplitude of vibration by the method just described may be combined with advantage in those cases in which the amplitude of the vigorous vibration is excessive.

In some cases it is not convenient to suppress the vigorous vibration by a movement of the mean position of the vibrator or by the method referred to above. In such cases, the amplitude of vibration can be controlled by increasing or decreasing the energy losses associated with the movement of the vibrator. For example, Fig. 7 illustrates a method of reducing the amplitude of vibration and extinguishing the vigorous vibration by induced eddy currents.

A suitably shaped electro magnet 31 is arranged to produce eddies in a conducting metal strip 32 passing between its poles. The current energising the magnet may be auto- or hand-controlled.

Fig. 8a represents an arrangement by means of which a gauge may be built which can be used to measure with accuracy distances which are greater than the amplitude of vibration of the flexible resilient member of the gauge. The feeler gauge surface (for example) is mounted on a frame which can be deflected (preferably so that the gauge surface 1 is moved in the plane of its vibration), for example, by a mass 33 sliding on a bar 34. The deflections of the surface 1 due to a given displacement of the mass 33 can be measured by the gauge shown at 4, 5, which operates in any one of the manners described above. In the figure the mounting of the gauge bracket ensures that it bends about the point 0, vertically below 1.

Fig. 8*b* represents another arrangement by means of which a gauge system 4—5—7—35 may be used to measure the distance between two surfaces. The gauge carries a double-faced gauge piece 35. This can be brought near to the surface of either of the test surfaces 37 by a device similar to that shown in Fig. 8*a*. It is clear that, knowing the length of the gauge piece 35 and the calibration of the gauge the distance between the test surfaces 37 can be found and changes in the length of the object 36 can be measured.

Any of the previous arrangements of the gauge may be adapted, if desired, to the measurement of the displacement of pointers of pointer-instruments. In this way the arrival of the pointer at any chosen point on the scale of the instrument can be registered with great precision (to 10^{-4} or 10^{-5} ins.), by providing the pointer with a contact gauge surface and placing a vibrating feeler gauge surface at any chosen point of the scale, the arrival of the pointer at this point being indicated with extreme accuracy by the setting in of the vigorous vibration. This make possible the " magnification " arrangement shown in Fig. 9. In this arrangement, the pointer of the current measuring instrument *m* is provided with a contact gauge surface which, at the zero position of the pointer, is in vibratory contact with a feeler gauge surface. The instrument *m* is deflected by the current the value of which is required; it is also deflected, but in the opposite direction by a very small fraction of an opposing current read on another current measuring instrument *m*, which current is derived from a large condenser 38 charged by a battery 39. When these two currents, passing in opposite directions through the instrument *m*, are exactly equal, the instrument *m* indicates zero, the pointer reaches the position in which the vibratory contact becomes operative, and this may be made to cause a relay to function. This relay opens the contact at *f* (or closes a contact at *h*) and so causes the current in the instrument m^1 to fall (or become nil) thus removing the pointer of the instrument *m* away from the gauge and so initiating the cycle of operations. The maximum indication of the instrument m^1 is a measure of the current deflecting the instrument *m*. Alternatively, the condenser 38 may be charged or discharged directly, (that is, without the intervention of a relay), by way of the gauging surface carried by the pointer of the current measuring instrument *m*.

By this means one micro ampere at *m* can be made to appear as a deflection of one milliampere at m^1.

It is preferable that the current measuring instruments *m* and m^1 should have a similar response to transient forces. Alternatively if m^1 is the more swiftly acting instrument it may be made sluggish by connecting condensers in parallel or by any other known means.

The fact that the pointer of the current measuring instrument *m* is not required to deflect more than a small fraction of an inch (or a fraction of a degree) permits the use of pointers without pivots, for example, of pointers the stem of which is flexible and rigidly fixed at one end, the other end being deflected by a force which is a known function of the quantity to be measured. This would simplify the construction of such instruments to a degree hitherto impossible.

The above devices provide methods and apparatus for micro-measurements hitherto unequalled for their accuracy and simplicity of technique. It will be understood that variations in details may be made to the apparatus described and to the electric circuits required for their operation, as well as applications of the methods and apparatus herein described to purposes not referred to, without departing from the spirit of the invention, as set forth in the statement of claims.

The operation of any apparatus provided with a device according to the invention may be made self recording, for example in a manner already described. The apparatus is connected as shown in Fig. 5, with a controlling circuit such as shown in Fig. 4*c*. The recording is effected by the instrument *m* in Fig. 4*c*. The recorder itself may be for example a spark or a pen recorder of any known type.

I am aware that, in a particular type of extensometer, the position of a measuring member with respect to a fixed datum mark is ascertained by the moment when the vibration of a vibratory element, set in resonant vibration by the finger, is damped when the said measuring member touches the said datum member.

It has also been proposed to ascertain the instant at which mechanical contact takes place between a fixed and a movable member by providing the latter with a vibrator the axis of which is perpendicular to the surface of the fixed member, so that the motion of the edge of the tip of the said vibrator is tangential to a plane parallel to the said surface, the motion of the vibrator being damped when the tip of the vibrator touches the said surface (Spilsbury, N.P.L. Report for 1922, p. 94).

These two devices make use of a vibrator in a manner entirely different from that described above, and which has nothing in common with the phenomenon of the setting in of a distinctive mode of vigorous vibration which is the fundamental feature of any apparatus according to my invention.

Having now particularly described and ascertained the nature of my said invention, and in what manner the same is to be performed, I declare that what I claim is:—

1. An apparatus for detecting, observing, measuring, indicating, recording or utilizing minute changes of position of a solid body, an essential feature of which is of the nature of a linear dimension gauge or like device, consisting of (1) a gauge carriage which is movable with respect to a supporting bed and (2) a contact-indicating device, comprising a "feeler gauge surface" (or surfaces) carried upon a flexible resilient member or "vibrator" maintained by any suitable means in a state of vibration, the amplitude of which is normally steady or controlled, said apparatus being characterised in that the said flexible resilient member is so proportioned and mounted upon the said gauge carriage that the frequency of one of its modes of natural or resonant vibration is near to (above or below) the frequency of the forces maintaining the said member in vibration, the difference between these two frequencies being assigned such a value that when a "contact gauge surface" carried by the body the displacement of which is to be detected, observed, measured, indicated, recorded or utilised, comes in close proximity to the "feeler gauge surface" (or surfaces), so as to touch it with a certain very small force of impact, there is set up a particularly distinctive mode of intermittent contact between the "contact gauge surface" on the body and the "feeler gauge surface" on the flexible member, so that the said flexible resilient member breaks into a new vigorous mode of vibration, which is characterised in this, that this new mode of vibration does not return to the steady or controlled mode of vibration when the contact gauge surface is brought back into the position it occupied when the initial impact occurred, and even when it is withdrawn slightly further away.

2. Apparatus as claimed in claim 1, in which the position of the contact and feeler gauges surfaces are interchanged, the resilient vibrating member carrying the feeler gauge surface being mounted on the solid body the displacement of which is under observation and the contact gauge surface being carried by a suitable fixed datum member.

3. Apparatus as claimed in claim 1 or 2, in which both the contact and feeler gauge surfaces are in a state of vibration.

4. Apparatus as claimed in any one of the preceding claims, in combination with means for obtaining and for controlling very small displacements of the feeler element for the purpose of fine adjustment.

5. Apparatus as claimed in claim 4, in which the fine adjustment is obtained by displacing the support of the vibrator.

6. Apparatus as claimed in claim 4, in which the fine adjustment is obtained by altering the mean position of the vibrator with respect to its support.

7. Apparatus as claimed in claim 4, in which the fine adjustment is obtained by changing the amplitude of vibration of the vibrator.

8. Apparatus as claimed in any one of claims 1 to 4, characterised in that the gauging operation is controlled by alternating forces only.

9. Apparatus as claimed in any one of claims 1 to 4, characterised in that the gauging operation is controlled by alternating and unidirectional forces combined.

10. Apparatus as claimed in claim 4, further characterised in that the setting in of the vigorous vibration is indicated by the chattering sound it produces.

11. Apparatus as claimed in claim 4, further characterised in that the hammering produced by the feeler gauge surface in the state of vigorous vibration is used to operate a visual indicating device.

12. Apparatus as claimed in claim 4, further characterised in that the vigorous vibration is used to affect a light-sensitive device.

13. Apparatus as claimed in claim 4, further characterised in that an auto-control of the gauging operation is provided, by which the vigorous vibration is automatically extinguished, thereby rendering possible a repetition of such operation so as to make the same cyclic.

14. Apparatus as claimed in claim 13, further characterised by means through which any increase in the amplitude of

vibration of the vibrator, due to changes in the alternating driving forces, is combined with a shifting of the mean position of the vibrator away from the contact gauge surface.

15. Apparatus as claimed in claim 13, in which control is effected by means of an electric current passing between the contact and feeler gauge surfaces.

16. Apparatus as claimed in claim 13, in which control is effected by means of a subsidiary jar-sensitive or " chatter " contact (or contacts) set in operation by the setting in of the vigorous vibration.

17. Apparatus as claimed in claim 13, in which control is effected by means of a relay which changes the mean position of the vibrator relatively to its support.

18. Apparatus as claimed in claim 13, in which control is effected by means of a relay which changes the amplitude of vibration.

19. Apparatus as claimed in claim 18, further characterised in that the change of amplitude is obtained by controlling the energy losses associated with the movement of the vibrator.

20. Apparatus as claimed in any one of claims 13 to 19, in which controlling means are provided which only permit steady but not sudden movements of the gauge device.

21. Apparatus as claimed in any one of the preceding claims, in which the vibration of the vibrator is produced by electromagnetic means.

22. Apparatus as claimed in claim 13, further characterised by a network containing a resistance combined with a condenser which charges up when the vigorous vibration begins, the P.D. across the terminals of this condenser being directly controlled in magnitude by the vibration of the vibrator and being the source of the controlling current.

23. Apparatus as claimed in claim 14 or 21, further characterised in that it is supplied with A.C. and with D.C. derived from the same source by rectification, the direction of the D.C. being such as to shift the mean position of the vibrator away from the surface gauged when the A.C. voltage rises.

24. Apparatus as claimed in any one of the preceding claims, in which the gauging surface is secured underneath the face of the vibrator so as to be turned towards the supporting base, the proportions of the several parts of the apparatus being so designed, in the known manner, that variations in the mean temperature of the said parts have no effect on the position of the said gauging surface with respect to the fixed base of the apparatus.

25. An apparatus as claimed in claim 18, comprising a " bridge " rectifier in series with one of the A.C. leads, the said bridge having across its diagonal not connected to the A.C. lead a large condenser shunted by a resistance in series with a contact adapted to open when the vigorous vibration sets in.

26. Apparatus as claimed in claim 19, in which the vigorous vibration is suppressed by means of an auto- or hand-controlled electromagnet adapted to produce eddy currents in a conducting member secured to the vibrator.

27. Apparatus as claimed in any one of the preceding claims, adapted to measure distances greater than the amplitude of vibration of the vibrator, in which the feeler gauge surface is mounted on a frame capable of being deflected in any suitable manner.

28. Apparatus as claimed in claim 27, in which the gauge surface is mounted on a frame deflected so that the said feeler gauge surface is moved in its plane of vibration.

29. Apparatus as claimed in claim 28, adapted to measure the distance between two gauge surfaces, comprising a double faced feeler gauge piece adapted to be brought near either of the two contact gauge surfaces.

30. A pointer instrument, the pointer of which carries a contact gauge surface the position of which is ascertained by means of the feeler element of an apparatus as claimed in any one of the claims 1 to 28, substantially as described.

31. Apparatus as claimed in any one of the preceding claims, in combination with a pivotless pointer measuring instrument without coiled spring or springs, the pointer of which is, for example, a flexible resilient strip fixed at one end and deflected by the forces to be measured.

32. In apparatus for detecting, observing, measuring, indicating, recording or utilizing minute displacements of a solid element, the use of a device as claimed in claim 1, constructed, connected and operated in one of the manners herein described, for the purpose set forth.

33. Apparatus and circuit connections, substantially as described and as shown in the appended drawings.

Dated this 11th day of December, 1934.

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First Avenue House, High Holborn,
London, W.C.1.

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Fig. 1.

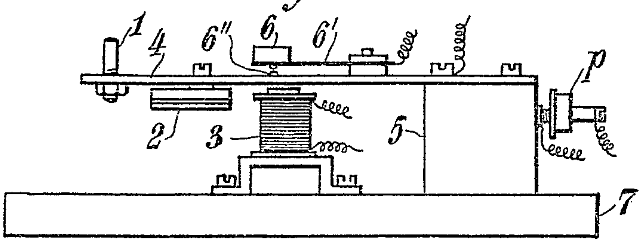


Fig. 2.

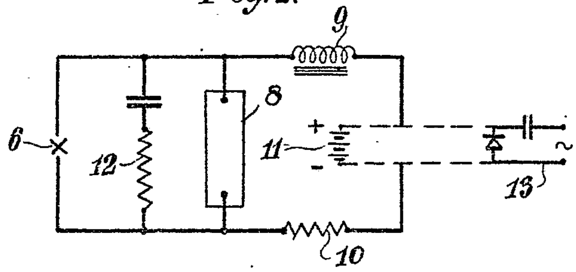


Fig. 3a.

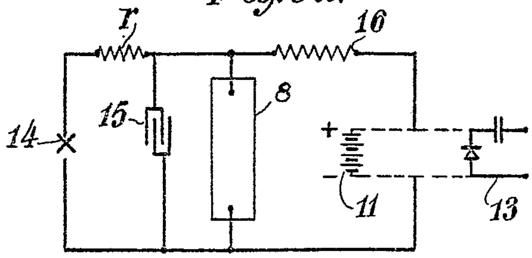


Fig. 3b.

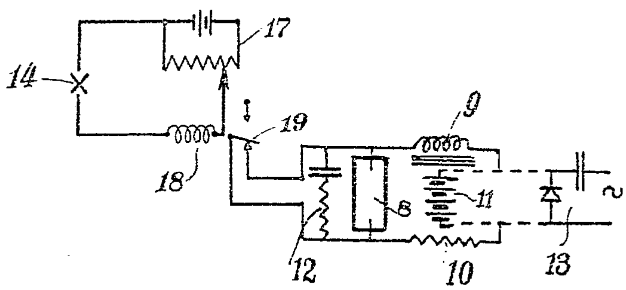


Fig. 4a.

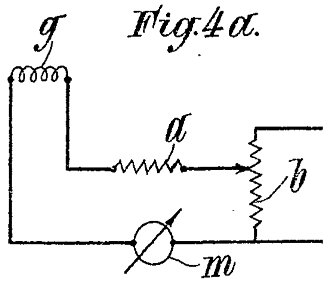


Fig. 4b.

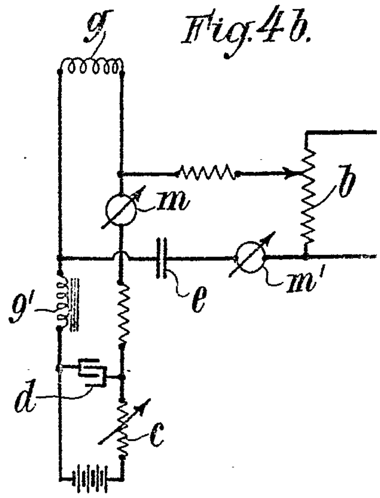


Fig. 4c.

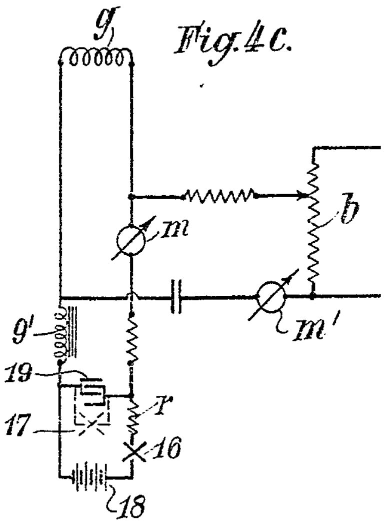


Fig. 4a.

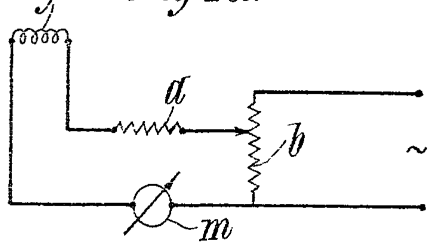


Fig. 4b.

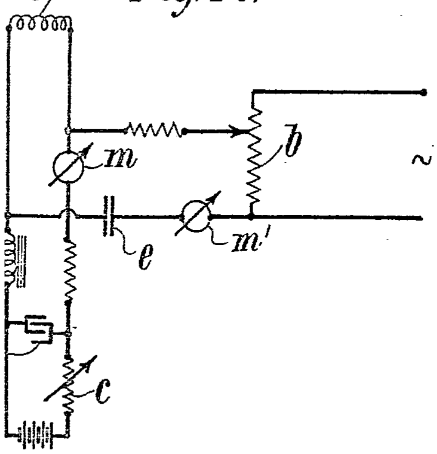


Fig. 4c.

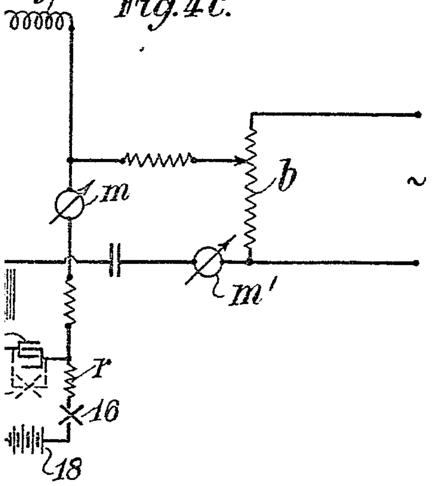


Fig. 4d.

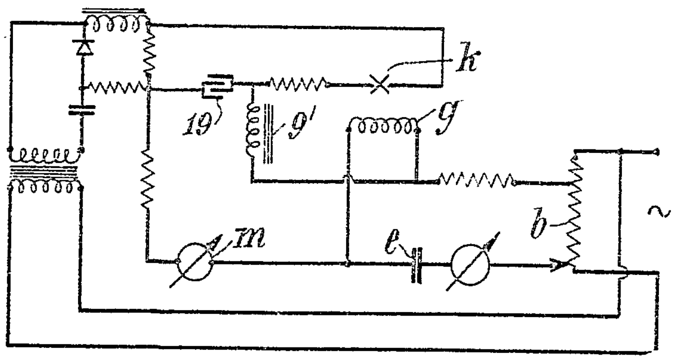


Fig. 5.

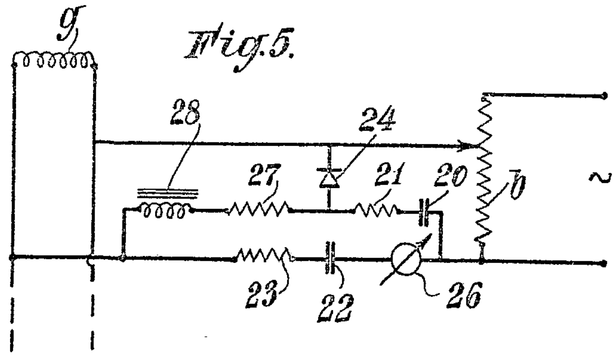


Fig. 6.

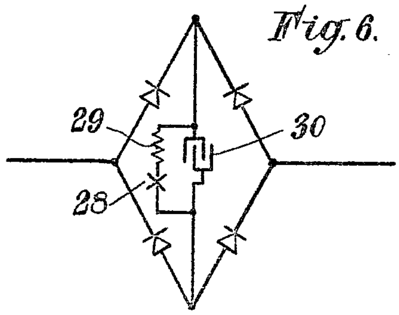
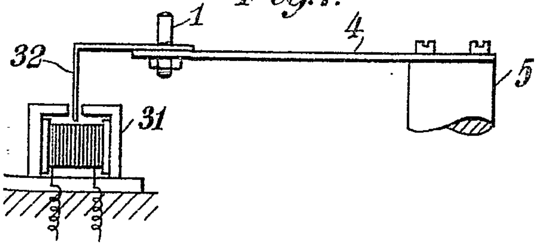


Fig. 7.



SHEET 1

Fig. 1.

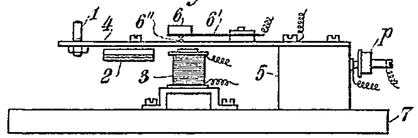


Fig. 2.

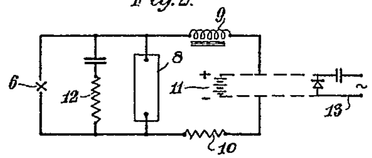


Fig. 3a.

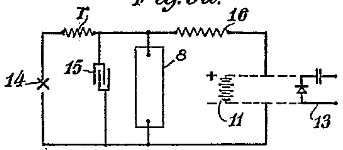
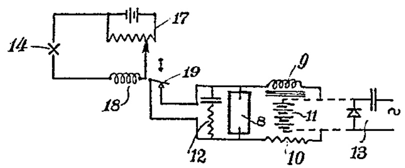


Fig. 3b.



SHEET 2

Fig. 4a.

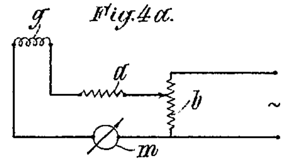


Fig. 4b.

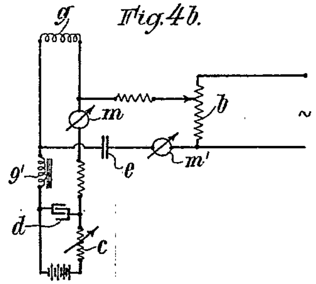
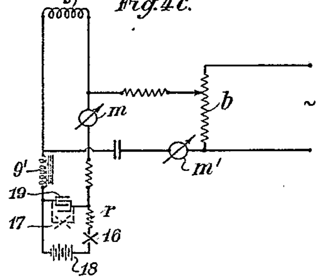


Fig. 4c.



SHEET 3

Fig. 4d.

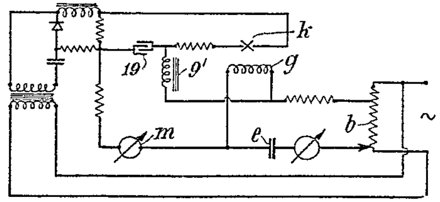


Fig. 5.

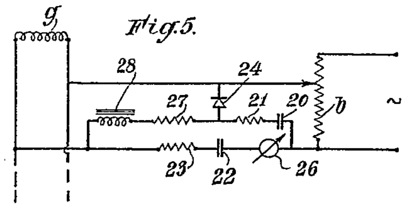


Fig. 6.

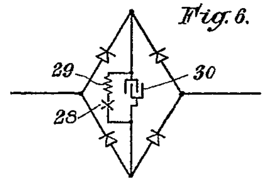


Fig. 7.

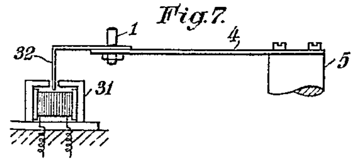


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Fig. 8a.

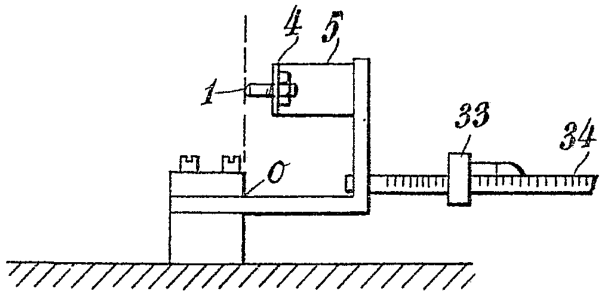


Fig. 8b.

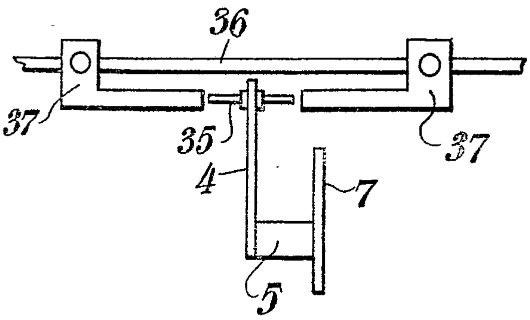
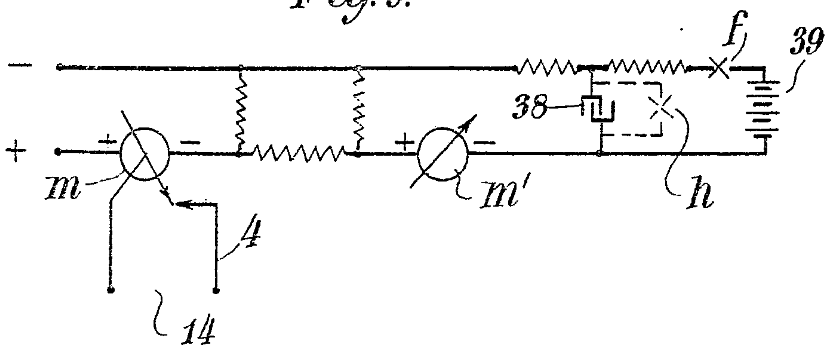
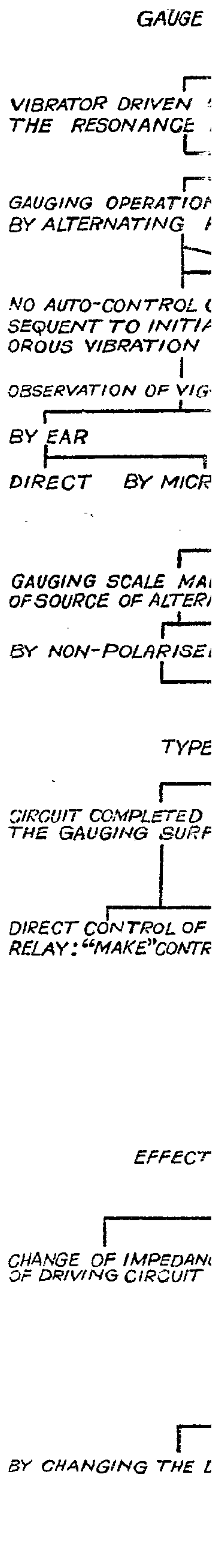


Fig. 9.





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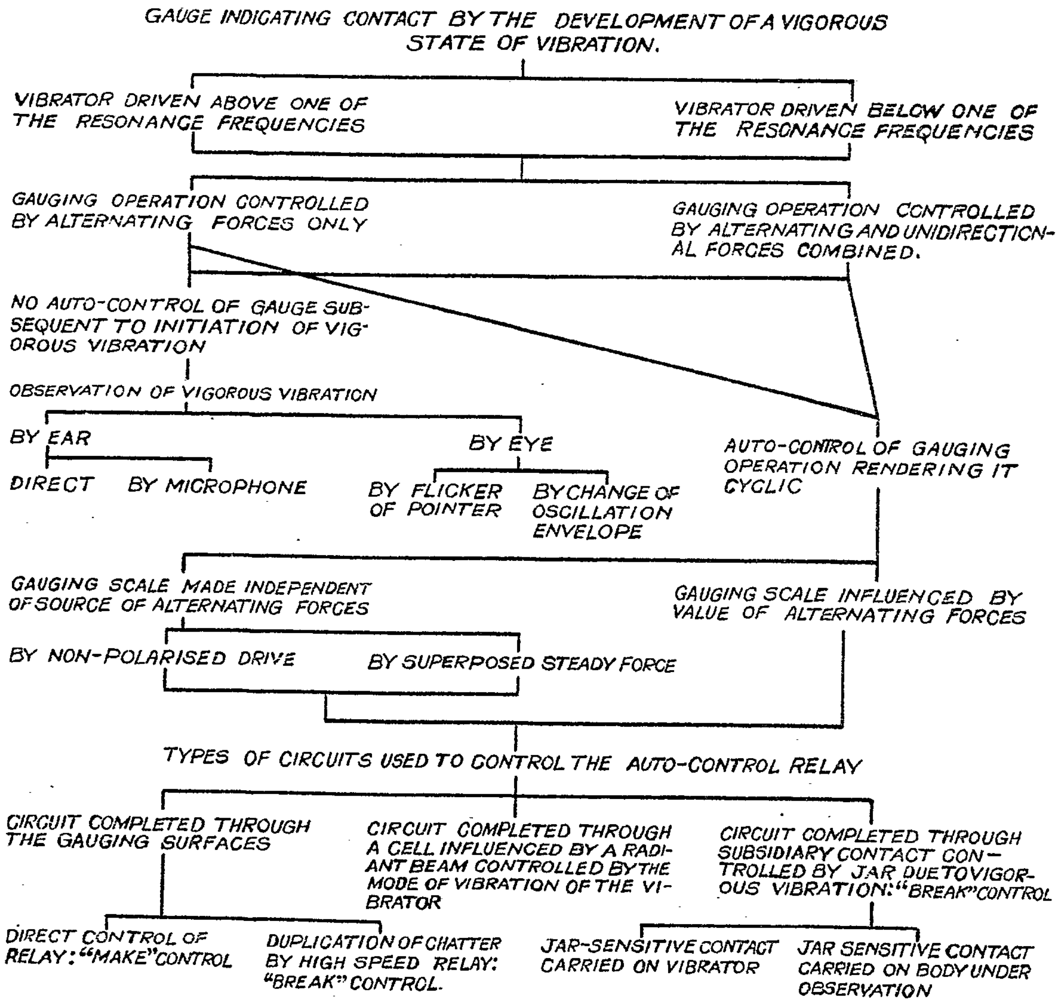

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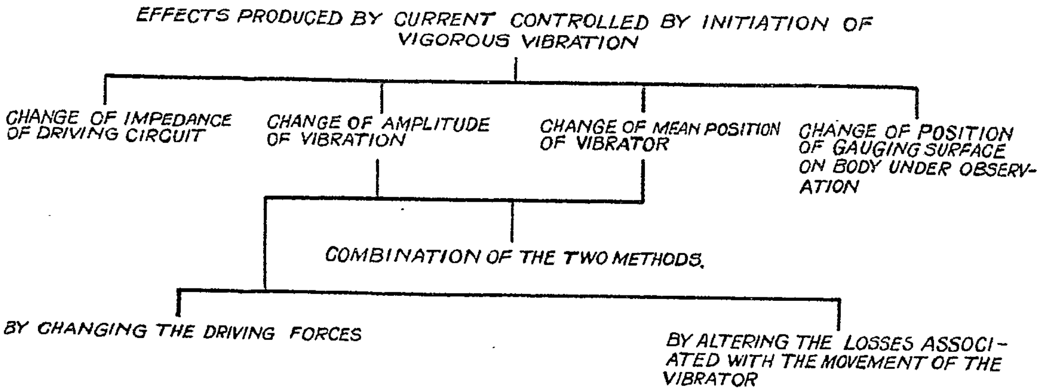


Fig. 8a.

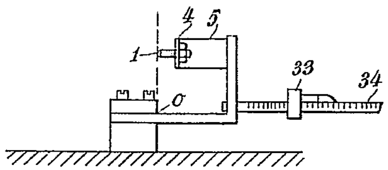


Fig. 8b.

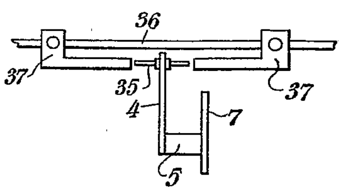
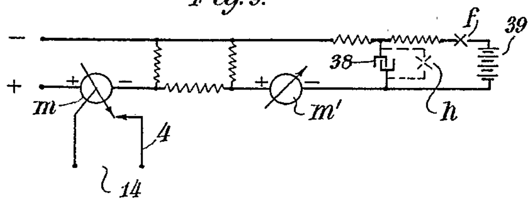


Fig. 9.



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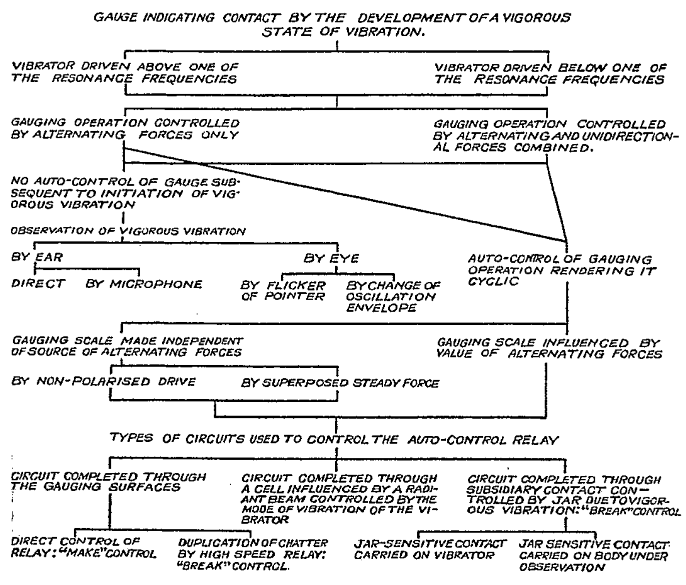

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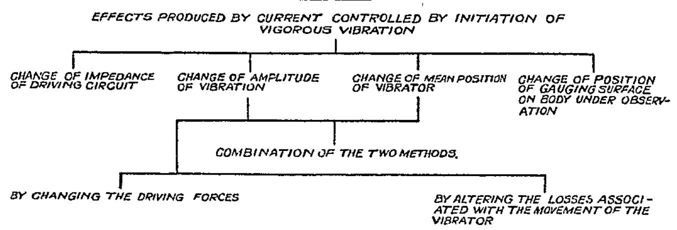

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