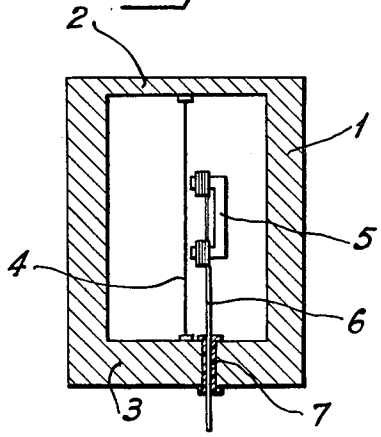
March 29, 1966 A. M. J. BELLIER 3,242,738

PRESSURE-RESPONSIVE INSTRUMENTS

Filed Feb. 12, 1963

Fig. 1



PRIOR ART

Fig. 2

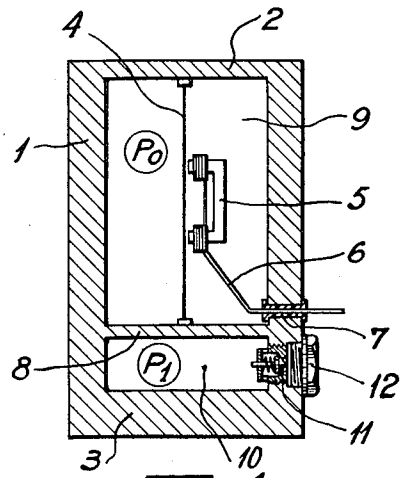
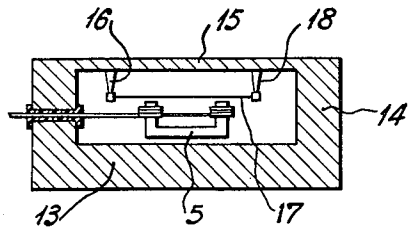


Fig. 3



PRIOR ART

Fig. 4

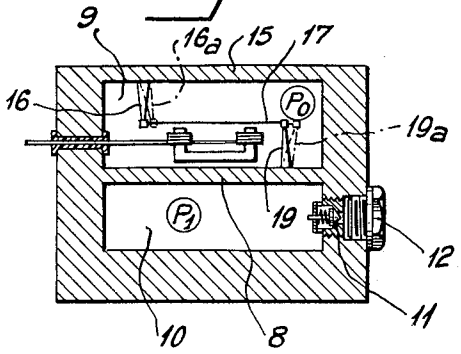
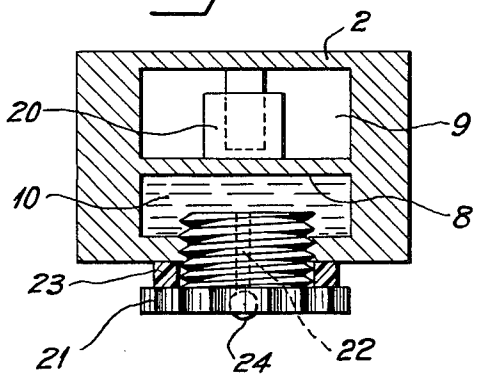


Fig. 5



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3,242,738

PRESSURE-RESPONSIVE INSTRUMENTS

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Claims priority, application France, Feb. 28, 1962, 889,516
4 Claims. (Cl. 73—393)

This invention relates to pressure-responsive instruments of the general type comprising a sealed casing having a pressure-responsive wall or diaphragm exposed to a variable pressure to be indicated, and deformation-responsive means within the casing and connected to said wall or diaphragm so as to respond to the deformations thereof by a corresponding change in a physical characteristic of said deformation-responsive means. For example, as described in the U.S. Patent 2,604,787 of which I am one of the applicants, the deformation-responsive means may comprise a vibratory element supported from said wall so that the vibrational frequency of the element will change when the wall is deformed due to a variation in the pressure to be indicated. Such instruments further comprise electrical pick-up means associated with said deformation-responsive means to sense said change in characteristic and transmit it to a remote point as an electric signal.

Objects of this invention are to provide pressure-indicating instruments of this general kind which will have higher accuracy and fidelity as well as greater ease in calibration and adjustment than conventional instruments of similar type, and specifically to provide in such pressure-indicating instruments improved temperature-compensating means which will be capable of completely or substantially eliminating thermal error, a source of erroneous indication which it has not been found practical heretofore to remove in an entirely satisfactory manner to the applicant's knowledge.

The description will now proceed with reference to the accompanying drawings, given for purposes of clarification and convenience only but not of limitation, and wherein:

FIG. 1 is a schematic sectional view of one form of conventional pressure transmitter instrument utilizing as the deformation-responsive element a vibratory string having one end attached to the pressure-responsive wall of the instrument so as to have its vibratory frequency change with deformation of said wall;

FIG. 2 is a corresponding view of an instrument of similar type but embodying the improvement of the invention;

FIG. 3 is a schematic sectional view of another form of conventional instrument wherein the deformation-responsive element is a vibratory string having both ends attached to the pressure-responsive wall so as to have its vibratory frequency change with variations in wall curvature;

FIG. 4 is a corresponding view of an instrument of this same type but incorporating the improvement of the invention;

FIG. 5 is a similar view of a further embodiment of the invention.

A known type of pressure-transmitter is illustrated in FIG. 1 as comprising a generally cylindrical casing **1** having relatively thick undeformable side walls and one end wall **3**, while its opposite end wall **2** is relatively thin so as to be deformable under the effects of a variable pressure to which said wall is exposed on its outer side. While wall **2** is shown integral with the casing **1** for simplicity, it will be understood that it would usually be provided as a separate diaphragm-like element suitably attached to the casing. A vibratory string **4** has its ends attached by

appropriate means to the centers of the opposite walls **2** and **3** and an electromagnet **5** is mounted within the casing through means not shown close to the midportion of the string **4**, with the electrical leads **6** connected to the electromagnet windings being led out of the casing through an aperture formed through wall **3** and having a suitable tubular sealing gasket **7**. The leads **6** are externally connected to a conventional electrical circuit arrangement capable of both applying pulses to the electromagnet windings to excite the string **4** into a sustained vibratory condition, and at the same time generating a voltage signal corresponding to the frequency of the resulting vibrations.

The operation of the device just described is well-known: When the string **4** is vibrated by means of the electromagnet **5**, its vibratory frequency is a function of its tension and hence of the axial distance between the centers of walls **2** and **3**. In the case of a change in the pressure acting on the outer side of the thin wall or diaphragm **2**, the string tension and hence its vibratory frequency and the electric signal derived in the circuit connected to leads **6** are varied correspondingly to provide a measure of the variation in said pressure.

The conventional device described is open to the following defects. The signal produced by the device is a true measure of the pressure acting on wall **2** only to the extent that the pressure of the body of air or other gas enclosed in the casing **1** remains constant, and moreover, that the initial distance between the opposite walls of the casing, i.e. the initial axial length of the casing, is itself constant. Variations in temperature however cause variations in both these factors.

In the first place, temperature variations vary the volume and hence the pressure of the body of gas sealed in the casing, so that the back pressure acting on the inner face of wall **2** in opposition to the pressure to be measured varies with temperature and modifies the response of the instrument. In the second place axial expansions and contractions of the casing wall material with temperature also result in modifying said response, unless the expansion coefficient of the casing material is made to be the same as that of the vibratory string **4**. Due to the thermal effects referred to, conventional pressure indicator instruments have either had to be provided with thermostatic means for maintaining them at a constant temperature, which is always a complicated expedient and in many cases an inapplicable one, or have been equipped with temperature-compensating means which have usually assumed the form of metallic compensator elements, made of materials having a different expansion coefficient from both the casing material and the material from which the deformation-responsive element such as the vibratory string **4** is made, such elements being interposed between the respective ends of the deformation-responsive element and the respective end walls of the casing. Such arrangements are complicated and relatively expensive, and their effectiveness is moreover restricted due to the fact that they are extremely difficult to adjust after manufacture of the assembly, so that in most cases users of the instrument have to remain content with a crude adjustment affording only a very poor compensation for temperature variations and hence a low degree of accuracy in the measurements.

The invention solves the problem of temperature compensation in a very simple and highly effective way, as will now be described with reference of FIG. 2. This figure illustrates an instrument generally similar to that shown in FIG. 1 and wherein corresponding elements have been designated by the same reference numerals as in this last figure. However, it will be noted that the end of string **4** remote from the end attached to the deformable wall **2**, instead of being attached to an unde-

formable end wall such as the wall **3** in FIG. 1, is attached to another elastically deformable wall **8** which separates the main chamber **9** of the instrument from an auxiliary or compensating chamber **10** provided in the lower part of the casing **1**, and containing a sealed body of gas, e.g. air, initially adjusted to a pressure different from the pressure in the main chamber, by means of an adjustable valve device **11** and **12**. As will be shown mathematically below, it is possible so to select the initial pressure in the auxiliary chamber **10**, that subsequent temperature variations will cause elastic deformations of the wall **8** such as to compensate exactly for the temperature-induced errors described above and so that the variations in tension of the string **4** will be a function only of the external pressure applied to the upper wall **2**.

The demonstration will first be conducted on the simplified assumption that the material of the casing **1** and the string **4** have similar coefficients of expansion. Let p_0 be the initial pressure in the main or measuring chamber **9** and p_1 the initial pressure in the auxiliary or compensating chamber **10**, i.e. the pressures in the respective chambers at the time they are sealed. Let f_0 and f_1 be the specific deflections of the walls **2** and **8** respectively, i.e. the change in deflection of the respective wall (axially of the casing) per unit change in the pressure differential acting across the wall. Let α be the expansion coefficient of the air or other gas enclosed in each of the chambers, which are assumed to contain the same gas.

Assuming a temperature variation t from the initial temperature at which the chambers were sealed has occurred, the pressure in the main chamber becomes

$$p_0'=p_0(1+\alpha t)$$

and in the auxiliary chamber

$$p_1'=p_1(1+\alpha t)$$

Thus, in case of an elevation in temperature the upper wall **2** will cave out due to the increase in pressure within the chamber of the instrument, and will deflect axially by an amount:

$$f=f_0(p_0'-p_0)$$

or

$$f=f_0p_0\alpha t$$

In an instrument constructed in the conventional manner shown in FIG. 1 this temperature-induced deflection of the elastically deformed wall **2** produces a corresponding increase in length, and hence in tension of the string **4**, since the opposite (lower) end of the string is stationary, so that its frequency of vibration rises and erroneous measurement results. On the other hand, in the improved instrument shown in FIG. 2, the wall **8** to which the lower end of string **4** is attached undergoes axial deflection and in accordance with the invention matters are so arranged that the wall **8** deflects in the same direction as wall **2**, so that the string **4** is subjected to a zero net change in length, and hence its tension and vibratory frequency both remain unaltered.

Specifically, wall **8** is exposed on its under side to the altered pressure p_1' and on its upper side to the altered pressure p_0' so that it undergoes a deflection f' given by the following equation:

$$f'=f_1(p_1'-p_0')-f_1(p_1-p_0)$$

or

$$f'=f_1(p_1-p_0)\alpha t$$

It is evident that in order to obtain zero net elongation for string **4** and hence accurate temperature compensation, it is necessary that we have

$$f'=f$$

or

$$f_1(p_1-p_0)\alpha t=f_0p_0\alpha t \qquad (A)$$

or further, solving for p_1:

$$p_1=\frac{f_0+f_1}{f_1}p_0 \qquad (B)$$

Equation (B) defines the relationship that should obtain between the pressures p_1 and p_0 in the main and auxiliary chambers in order to achieve accurate temperature compensation. Thus, knowing the initial pressure p_0 in the main chamber and the specific deflections f_0 and f_1 of walls **2** and **8**, the pressure in auxiliary chamber **10** can be initially adjusted to the value p_1 through the valve **11** in order to ensure that the subsequent pressure readings of the instrument will not be impaired by any temperature variations liable to occur.

Where the unit or specific deflections of both walls are equal ($f_0=f_1$) the above relation simplifies to

$$p_1=2p_0$$

i.e. the initial pressure in the auxiliary chamber should be twice the initial pressure in the main chamber. Ordinarily however f_0 and f_1 will differ somewhat, since it is found difficult in practice to provide both walls or diaphragms exactly identical in shape and dimensions and with identical attachment characteristics to the casing. This constitutes no difficulty however since it is an easy matter to determine the deflection characteristics of the end walls in a simple calibration step (rather than by an uncertain calculation) and then select the proper pressure valve p_1 in accordance with equation (B).

Now departing from the simplifying hypothesis made above, it will be assumed that the expansion coefficient of the casing material is different from that of the vibratory element **4**, as will usually be the case. It will be evident from the previous discussion that in such a case, the above analysis will still remain true provided an extra term is added to the second member of equation (A) above, which term will represent the additional elongation undergone by the string **4** due to the differential axial expansion of the casing walls **1** relative to the string, and which term is positive if the casing material has a higher expansion factor than the string, negative if the reverse is true. More precisely, designating β the differential expansion coefficient of the casing material relative to the string material, and h the common axial dimension of casing and string, the additional elongation imposed on the string by the differential thermal expansion effect is

$$\beta ht$$

so that the full compensation equation to replace equation (A) above becomes

$$f_1(p_1-p_0)\alpha t=f_0p_0\alpha t+\beta ht \qquad (C)$$

and the full equation solved for p_1, replacing (B) above, is

$$p_1=\frac{f_0+f_1}{f_1}p_0+\frac{\beta h}{\alpha f_1} \qquad (D)$$

Thus there is again provided a well-defined pressure value p_1 which may be exactly deduced from the actual physical and elastic characteristics of the components by means of tests applied to the complete instrument prior to delivery to the customer, and the pressure in the auxiliary chamber **10** may then be adjusted to such value to ensure accurate temperature compensation throughout the subsequent service life of the instrument.

The inventive concept involving the provision of an auxiliary chamber in which the fluid pressure is selected to a specific value selected to afford substantially complete thermal compensation is applicable to many types of pressure indicator structures other than that shown in FIGS. 1 and 2. Thus, FIG. 3 shows another conventional instrument wherein the deformation-responsive element, in this case also a vibratory string, though it might assume other forms, is so mounted as to measure the deflectional curvature of the pressure-responsive element or wall rather than the axial deflection at the center of the wall as in FIG. 1. In the FIG. 3 device, there is

provided a cylindrical casing having side walls **14** and bottom wall **13** which are substantially undeformable, and an elastically deformable opposite end wall **15** providing the pressure-responsive element or diaphragm. A vibratory string **17** constituting the deformation-sensing element is supported in the casing by means of a pair of arms **16** and **18** attached to both of its ends and both projecting from the wall **15**, so that it extends parallel to the plane of said deformable wall rather than normally to it as in the devices first described. An electromagnet **5** is mounted adjacent to the string **17** in a relationship with respect thereto generally similar to that described for magnet **5** relative to string **4** in FIG. 1. Deflection of wall **15** due to variations in external pressure applied to the outer surface of the wall will cause variations in curvature of the wall and hence corresponding variations in the tension of string **17**, producing variations in its vibrational frequency and hence in the electric output signal produced. It will be obvious that the instrument thus constructed is open to the same drawbacks in regard to temperature effects as the instrument shown in FIG. 1, and according to the invention it is modified in the manner illustrated in FIG. 4 now to be described.

In this case as in the embodiment shown in FIG. 2, the casing of the instrument is provided with an additional compensating or auxiliary chamber **10** and the partition wall **8** separating this auxiliary chamber from the main chamber is made elastically deformable. The vibratory string **17** instead of having both ends supported from the pressure-responsive end wall **15**, has only one of its ends supported from this wall through the arm **16**, while its opposite end is supported by means of arm **19** from the wall **8**, the arrangement being such that the general direction of the string is parallel to the end wall surfaces as in FIG. 3. The auxiliary chamber **10** is filled with gas at a pressure which is initially adjustable through valve **11** provided with cap **12**, to a value higher than that in the main chamber. It can again be shown by an analysis analogous to that presented earlier that the pressure in chamber **10** can be selected such as to achieve the desired compensation. The full analysis need not be given, and it should be sufficient to note that any increase in internal pressure in both chambers due to temperature elevation, will cause upper wall **15** to cave out upwards, so that the supporting arm **16** is deflected to a position such as **16***a*, while simultaneously the auxiliary end wall **8** will also cave upwards so that arm **19** assumes a position such as **19***a* and it will be evident from the geometry of the arrangement shown that the respective arms deflect in such directions that the distance between their free ends tends to remain the same, and may in effect be made to remain the same provided the pressure in the auxiliary chamber is properly selected with regard to the main chamber pressure and the deflection characteristics of the deflectable walls. The additional error-producing effect of differential expansion between the material of wall **15** and that of the string **17** can also be fully compensated for.

With pressure-indicating instruments designed for the measurement of high pressures, the initial internal pressure p_0 in the measuring chamber must be high. It is evident from the equations given above that the initial pressure p_1 to be provided in the auxiliary chamber such as **10** of a modified instrument according to the invention must be considerably higher still, or else the unit deflection of the inner wall **8** considerably increased. Both alternatives are undesirable.

An additional difficulty arising where both pressures p_0 and p_1 are high, is that volume variations of the main and auxiliary chambers **9** and **10** due to variations in the external pressure acting on the pressure-responsive wall, are no longer negligible. This results in a reduction in the sensitivity of the instrument and moreover erratic temperature compensation due to the pressure p_1 in the compensating chamber of the invention being variable.

The above difficulties are overcome in accordance with an aspect of the invention by using a liquid instead of gas as the fluid in the compensating chamber.

The effectiveness of such an arrangement can be shown by the following simplified analysis wherein the same notations are used as in the analysis referring to FIGS. 1 and 2, and wherein, moreover, V_1 will designate the initial volume of the auxiliary chamber **10** and V_1' its altered volume at a temperature t different from the temperature at which the chamber was initially sealed. Furthermore, γ will be used to designate the differential volume expansion coefficient of the liquid filling chamber **10** with respect to the material forming the walls of said chamber.

The change in volume of the auxiliary chamber due to the assumed change in temperature is

$$V_1'-V_1=\gamma t V_1$$

If we put

$$V_1'-V_1=Kf'$$

K being the ratio of volume increase of the auxiliary chamber to variation in deflection of wall **8** which produced such increase, then we have

$$f'=\frac{\gamma t V_1}{K}$$

and the compensation equation ($f=f'$) becomes

$$\frac{\gamma}{K}V_1=f_0 p_0 \alpha$$

Thus, the initial volume V_1 of the auxiliary chamber required to provide the desired compensation can be determined from this equation when the other factors have been determined by suitable tests.

In accordance with this aspect of the invention, it would clearly be desirable to be able to adjust the initial volume V_1 of the auxiliary chamber, and FIG. 5 illustrates an embodiment of the invention in which this is provided for. The pressure indicating instrument shown in that figure comprises a cylindrical casing generally similar in shape to that shown in FIG. 4, with two adjacent separate chambers, a main or measuring chamber **9** and auxiliary or compensating chamber **10**. The upper end wall **2** of the measuring chamber **9** is elastically deformable and its outer face is exposed in use to the pressure to be measured. The intermediate wall or partition **8** between the two chambers is also elastically deformable, while the cylindrical side walls and the lower wall of the casing are substantially undeformable.

Mounted within the upper chamber **9**, in which a body of gas, e.g. air, is sealed at a predetermined pressure as earlier explained, is a deformation-responsive device **20** which may be a vibratory string as described in connection with the previous embodiments, but is here shown schematically as an inductive or a capacitive pickoff or signal generator in two parts, having one part secured to the upper deformable wall **2** and its other part secured to the intermediate deformable wall **8**. The details of the pick-off are not illustrated since such devices are well-known. Briefly, the pick-off device **20** may include two capacitor electrodes respectively connected for movement with the walls **2** and **8**, and connected through conductor means not shown to an external circuit which applies different potentials to the respective electrodes, and senses variations in the capacitance between the electrodes, due to relative movement between the upper and lower parts of the pick-off device in response to variation in the pressure applied to the outer side of wall **2**, to produce an electric signal which is a measure of such variations. Alternatively, the pick-off device **20** may be inductive, e.g. a variable

transformer, in which case the lower part of the device, attached to wall 8, may comprise a first magnetic core with primary and secondary windings thereon, and the upper part of the device, attached to wall 2, may comprise a plunger-type core relatively movable in a recess of the first core to vary the saturation characteristic of the transformer and hence the output voltage induced in the secondary windings thereof as a function of the relative position between the two cores and hence of the pressure applied to the wall 2.

It is again emphasized that regardless of the nature of the deformation-responsive device used, the pressure readings derived therefrom in the guise of an electric signal would be subject to thermal error in the absence of the compensating means of the invention. In the embodiment of FIG. 5, the compensating means comprise a body of liquid, e.g. oil, sealed within the lower chamber 10. To permit adjustment of the effective volume of the compensating chamber 10, it is formed with a threaded opening of relatively large diameter in its bottom wall, and a screw plug 21 is adjustably screwed into this opening so that rotation of the plug will adjust the inner volume in chamber 10 available to the liquid. The plug 21 is provided with an axial bore 22 for the delivery of liquid to fill the chamber 10, the bore 22 being thereafter sealable with a seal 24, e.g. of thermosetting resin. An annular seal 23, e.g. of similar material is provided around the plug 21. The volume coefficent γ of thermal expansion of the compensating liquid in chamber 10 may be adjusted by suitable selection of the liquid used, and/or by injecting a small amount of gas to form a bubble in the liquid body, increasing the volume of such a gas bubble being equivalent to increasing the expansion coefficient of the liquid.

In a device using the compensating arrangement shown in FIG. 5, the compensating chamber 10 need not be substantially pressurized in the idle or initial state. Since the liquid used as the compensating fluid in this embodiment is substantially incompressible, the desired high deflection characteristic can still be imparted to the compensating wall 8, without having to use high pressure values in the body of compensating fluid, as was shown to be necessary in cases where the compensating fluid was a gas, as in the embodiments of FIGS. 2 and 4. Thus the previously mentioned difficulties are overcome and an instrument is made available which can be used to measure very high pressures without requiring the establishment of prohibitively high initial pressures in the compensating chamber.

It will be evident from the foregoing disclosure that the invention has provided a pressure-indicating instrument provided with means for fully and accurately compensating for temperature errors, which means are especially simple and inexpensive to construct and maintain and easy to calibrate and adjust for maximum effectiveness. It will also be obvious that the invention is capable of wide application to pressure-sensitive devices other than of the types shown and described herein. In addition to the three types of deformation- or strain-responsive pick-off arrangements specifically mentioned above, namely the vibratory-string, variable-transformer and variable-capacitance types of pick-offs, other kinds will suggest themselves, such as variable-resistance and variable-reactance, magnetostrictive, and the like. Various types of strain gauges may likewise be applied, e.g. of the wafer type adapted to be directly bonded adhesively to the wall 2 to which the variable pressure is applied, so as to measure the deflection of said wall as a measure of such variable pressure.

With the use of such wafer- or strip-like strain gauges, the invention contemplates an embodiment wherein a pair of such strain gauge wafers are bonded respectively to the external deformable wall such as 2 exposed to the variable pressure, and to the intermediate deformable partition wall such as 8 exposed to the compensating pressure, and such strain gauges are connected in a common electrical output circuit, such as a balanced bridge circuit, so as to effect the desired temperature compensation. It will be noted that in such an embodiment of the invention, it is not necessary that the measuring wall such as 2 and the compensating wall such as 8 are made parallel. Various other changes and modifications departing from the embodiments shown or mentioned above may be conceived without exceeding the scope of the invention as defined in the claims.

What I claim is:

1. A pressure-responsive instrument comprising a generally cylindrical casing having substantailly rigid undeformable side and one end wall, and an elastically deformable other end wall; an elastically deformable partition wall in said casing cooperating with said end walls to define a first and a second chambers in said casing; a body of gas sealed in said first chamber at a determined initial pressure; a body of fluid trapped in said second chamber at a determined initial pressure relatively higher than said first mentioned pressure; means passing through said casing for adjusting initial conditions of said fluid; strain-sensing means having a part attached to said one end wall and another part attached to said partition wall; whereby a physical characteristic of said strain-sensing means is varied on relative deformation between said deformable walls, and electrical pick-up means connected to said strain-sensing means and connected to an external circuit for producing a variable signal as a measure of said characteristic, and hence as a measure of said pressure acting on said one deformable end wall substantially compensated for variations in temperature to which said instrument is subjected.

2. A pressure-responsive instrument comprising casing means defining a measuring chamber having a first deformable wall exposed to a variable pressure and a compensating chamber having a second deformable wall in common with said measuring chamber; deformation sensing means comprising a vibratory string having its respective ends connected to said first and second walls, whereby relative displacement between said walls due to deformation thereof in response to variations in pressure and temperature will vary tensioning of said string; electromagnetic means connected to an external circuit for setting said string into sustained vibrations and for indicating the frequency of said vibrations; and a body of fluid in said compensating chamber and means passing through said casing for adjusting the initial conditions of said fluid so that on subsequent change in temperature said second wall will deform in a sense and by an amount substantially offsetting the effects on said characteristic of the corresponding temperature-induced deformations of the first wall, whereby said frequency will be a measure substantially only of the variations in said pressure.

3. An instrument as claimed in claim 2, wherein said walls are generally parallel, and said string has its ends attached to facing points of said walls and extends normally thereto.

4. An instrument as claimed in claim 2, wherein said walls are generally parallel, and said string has its ends attached to the free ends of respective mounts projecting from said walls and extends generally parallel to said walls.

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