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(54) METHOD OF DETECTING OR MEASURING VIBRATIONS

(71) We, KUREHA KAGAKU KOGYO KABUSHIKI KAISHA, a Japanese Company, of No. 1-8, Horidome-cho, Nihonbashi, Chuou-ku, Tokyo, Japan, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

This invention relates to a method of detecting or measuring vibrations using a piezoelectric element of an organic polymeric material.

Various types of pick-ups for use with vibrometers employing various principles have been proposed such as a capacitance type, a magnetostrictive type, a photoelectric type, a piezoelectric type using inorganic crystals or ceramics and a strain gauge type using resistor wire or the like.

Each of these prior vibrometer pick-ups has, however, inherent disadvantages. Pick-ups other than those of a piezoelectric type are particularly complicated in their structures and difficult to design. Moreover, even with a known piezoelectric pick-up of relatively simple structure, as well as with other types of pick-ups, there are inevitable limitations in measuring the vibration body at a desired location or if it has a complex surface configuration. In addition, capacitance, magnetostrictive photoelectric and known piezoelectric type pick-ups have the defects that their resonance frequency is low and the region of the measuring frequency is narrow because of their considerable mass and that said mass affects the vibrations of the vibration body to be tested.

We have succeeded, by the use as a gauge element of a piezoelectric material composed of particularly organic polymer materials, in developing an excellent pick-up for a vibrometer which can follow changes in distortion even with vibrations of very high frequency with high fidelity and with little or no effect upon the vibrations of the vibration body to be tested because of its extremely light weight and which can measure the

vibrations at any desired location of the vibration body and with any surface configuration thereof.

Moreover, since the piezoelectric materials of the present invention have a low linear elastic coefficient and take the form of thin film, no great stress is required for the displacement and the vibrations of the vibration body are not affected.

While conventional Rochelle salt, quartz crystal and piezoelectric ceramics (PZT, for example), have linear elastic coefficients ranging from 20 to 80×10^{10} dyne/cm², the piezoelectric material of high molecular weight according to the present invention is a very soft substance and the linear elastic coefficient thereof may be less than 5×10^{10} dynes/cm² even including electrodes. This may be used in a thin film of less than 100 microns thickness, in particular, less than five microns thickness. Since it is difficult to obtain a thin inorganic film of less than 100 microns thickness, this means that an extremely soft film which is several tens of times as soft as a conventional film can be obtained.

Accordingly, a piezoelectric element of polymeric materials as opposed to, for example, ceramics can not only be fabricated as a very thin film with any desired configuration, but can also precisely follow up changes in the distortion with the vibrations in an extremely high frequency region because of its extreme light weight and does not affect the vibrations of the vibration body to be measured because of its low linear elastic coefficient.

According to the present invention there is provided a method of detecting or measuring vibration which comprises forming an electric circuit including as a piezoelectric element electrodes having therebetween a piezoelectric material of a polyvinylidene fluoride resin, coupling said piezoelectric element at least partially to a vibration body, the vibration of which is to be detected or measured, and detecting or measuring the mechanical vibrations as changes in electrical charge or

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in voltage emitted by said piezoelectric material.

The present invention further provides a piezoelectric apparatus for detecting or measuring vibration, which comprises a piezoelectric element including a piezoelectric material of a polyvinylidene fluoride resin disposed between two electrodes, a detector means for detecting a voltage variation between said electrodes and means for securing the piezoelectric element to a vibration body, the vibration of which is to be detected or measured.

We have found that the apparatus according to this invention can measure or detect even small vibrations with high sensitivity and accuracy.

The present apparatus can detect slight changes in vibrations of the vibration body to be tested and, therefore, can be utilized for detecting changes in vibrations with elapsed time and abnormal vibrations, as well as for determining distribution of stress exerted on each of the various portions of a vibration body as it vibrates by mounting a piezoelectric element according to this invention upon the corresponding portions of said vibration body. It is also applicable to detecting so-called "cavities", that is, the difference in internal densities in steel materials and the like by applying certain vibrations to the materials and measuring the differences in the vibrations at different portions thereof.

Embodiments of the present invention will now be described with reference to the accompanying drawings in which:

Fig. 1 is a perspective diagrammatic view of the piezoelectric effect of a piezoelectric element of organic polymer material used in this invention;

Figs. 2, 3 and 4 are block diagrams of measuring circuits illustrating embodiments of the method of detecting or measuring vibration according to this invention; and

Fig. 5 and Fig. 6 are block diagrams of embodiments of vibration detecting or measuring apparatus according to this invention.

It is known that polar substances of high molecular weight such as polyvinylidene fluoride (referred to as PVDF hereinafter), polyvinylfluoride, polyvinylidene chloride, polyvinylchloride, Nylon 11 and the like can provide a piezoelectric material by applying to a sheet or film thereof a polarization effect such as by applying a high static electric field under heating.

Any of these piezoelectric materials exhibits piezoelectric effects of the expansion type. In Fig. 1 axes X_1 , X_2 and X_3 indicate the directions of orientation, width and depth respectively in a piece of piezoelectric material. In a piezoelectric material produced from a mono-axially orientated film or sheet, a significant piezoelectric effect can

be observed as polarization d_{31} (d represents the piezoelectric constant) along the axes X_3 when the stress is applied along the axis X_1 shown in Fig. 1.

Although d_{32} is not zero, it is usually only of the order of from $1/10$ to $1/20$ of d_{31} .

This anisotropy is scarcely found in a non-orientated or biaxially orientated film or sheet.

We have found that a sheet or film made of PVDF series resin processed under properly chosen conditions can provide a piezoelectric body having a piezoelectric constant d_{31} of more than 1×10^{-7} cgsesu (maximum 2×10^{-6} cgsesu) with mono-axial orientation and of more than 5×10^{-8} cgsesu with non-orientation or biaxial orientation thereby providing a film of wide applicability. PVDF series resins, of course, include copolymers thereof comprising PVDF as basic component. Organic piezoelectric materials are described and claimed in our copending Patent Applications Nos. 44744/71, 56093/71 and 33861/72 (Serial Nos. 1,339,295, 1,349,860 and 1,367,738).

In PVDF material, it is desired to select and polarize a film of beta-type crystal structure since it provides an especially high piezoelectric constant. Such a piezoelectric film has piezoelectric characteristics of the expansion-contraction type which are quite different from those of stretched synthetic polypeptide films which have piezoelectric characteristics of Face Shear type such as are disclosed in French Patent Specification No. 2,000,770. A special design is required for an element of the latter type and in the construction of Fig. 2 of the accompanying drawings, for example, wherein the piezoelectric body is provided with electrodes at both sides thereof, such a stretched synthetic polypeptide film can deliver only extremely low signals as a vibration pick-up because the signals in the different phases meeting at right angles off-set with each other. Moreover, it has been confirmed that the piezoelectricity thereof is small.

Methods of use of a vibrometer pick-up in which a piezoelectric body of a PVDF resin is used as a gauge element will now be described with reference to Figs. 2 to 4 of the accompanying drawings.

In Fig. 2, reference number 1 designates a piezoelectric body of a PVDF resin employed as a gauge element and having conductive electrodes 2 and 2' on both sides thereof provided by any suitable process such as vapour deposition of metal. An adhesive layer 3 consists of double sided adhesive tape or of a suitable adhesive and is used to attach the gauge element to a vibration body 4 to be tested. Simply, the adhesive layer 3 may be prepared by applying suitable pressure-sensitive adhesives to

the surface of the electrode 2¹ and contacting the same with a peelable protective sheet film. Then, the piezoelectric element is used by peeling off the said protective sheet.

The materials employed as the adhesives or as the great adhesive tapes should, of course be selected so that no great stress is required for their distortion as compared with that of the vibration body to be tested. The gauge element may be mounted upon the vibration body to be tested by means other than adhesives. The vibrations are applied to the pick-up, for example, in the direction shown by the arrow in Fig. 2.

In measuring the vibrations of the vibration body to be tested in a certain direction, a piezoelectric body of a PVDF resin produced from a mono-axially orientated film may be used as the gauge element if aligned in the direction of orientation of the vibrations.

In measuring the vibrations in unspecified directions, a piezoelectric body of a PVDF resin having no piezoelectric anisotropy and produced from a non-orientated or biaxially orientated film is preferred to be used as the gauge element.

The electric field generated by such vibrations is delivered through an adequate impedance conversion circuit 5 and measured or detected by a measuring or detecting device 6 such as a voltmeter, recorder, oscilloscope or the like, and the displacement produced in the vibrations is determined by way of predetermined relationships between distortion and output voltage in the pick-up. In addition, by the use of a recorder or oscilloscope, frequency can be measured and accurate wave form can be measured by using a suitable integration circuit.

In Fig. 3, the piezoelectric body 1 of a PVDF resin has electrodes 2, 2¹ on both sides thereof and is partially attached to the vibration body 4 to be tested by way of adhesive materials 3, 3¹. The pick-up may be mounted to the vibration body 4 in any suitable way such as small screws or clamping means in addition to adhesion.

The piezoelectric body 1 of PVDF resin employed as the gauge element may be coupled at one end thereof to the vibration body 4 to be tested and fixed at the other end thereof to a stationary body 7 as shown in Fig. 4. In Fig. 4, the numeral 1 designates a piezoelectric body of a PVDF resin weight having conductive electrodes 2, 2¹ on both sides thereof provided by any suitable process such as vapour deposition of a metal film. One end of the pick-up is adhered by double sided adhesive tape or by adhesives 3 or fixed by conventional securing means such as small screws, clamps, etc., to the stationary body 7.

The other end of the pick-up is fixed to

the vibration body 4 to be tested, in the same way as said one end is secured to the stationary body 7. The vibrations of the vibration body 4 shown by the arrow are thus transmitted through this construction to the pick-up.

In this embodiment of the vibration measurement device according to the present invention, one end of the pick-up is secured to the stationary body and the changes in the distance between the vibration body to be tested and the stationary body are equal to the displacement applied to the entire length of the pick-up. Therefore, a large displacement is exerted on the pick-up producing a high output voltage and thus enabling measurement or determination of even extremely weak vibrations of the vibration body to be tested.

The apparatus according to this invention is very simple in its construction, capable of measuring an extremely wide frequency range, and the frequency characteristics thereof are flat over a wide frequency range. Moreover, it has high sensitivity and accuracy because of its high output voltage. It should particularly be noted that the apparatus according to this invention can be fabricated inexpensively notwithstanding the foregoing highly advantageous features.

It is desirable to apply a shield to the entire pick-up system according to this invention when it is used for measuring to prevent electrical noise as far as possible, because the presence of an electric field or changes in the capacitance, if any, in the vicinity thereof, may cause errors in measuring.

In the method according to this invention described above, a FET (field effect transistor) is desirably used in an impedance conversion circuit and a complete detecting or measuring device is formed by combining these elements.

An embodiment of apparatus according to this invention will now be described with reference to Fig. 5, wherein a piezoelectric element 1 of a PVDF resin is provided with electrodes 2, 2¹ on both sides thereof. Numeral 8 designates a FET circuit and 6 designates a measuring or detecting device.

In using this apparatus the piezoelectric element 1 of PVDF resin which is provided with electrodes is mounted upon the vibration body 4, the vibration of which is to be detected or measured, in a manner as hereinbefore described. The changes in vibrations of the vibration body to be detected are thus converted into a varying voltage by said piezoelectric body.

The voltage generated is delivered, through the FET circuit 8 and measured or detected by a measuring or detecting device 6 such as a voltmeter, recorder oscilloscope, or the like.

It can also actuate an alarm employed in combination with a relay circuit. More specifically, a piezoelectric body of a PVDF resin is partially or entirely coupled to the vibration body to thereby transform the changes in the vibrations into a varying voltage. If a predetermined voltage level is exceeded by the generation of abnormal vibrations or the like, the alarm connected to said piezoelectric body is actuated to warn of the abnormal vibrations in the vibration body. For the above construction, the FET circuit is provided between said piezoelectric body and the relay circuit for the actuation of the alarm in order to alter the impedance so that the relay circuit connected to the alarm may be operated by the voltage produced in the piezoelectric body.

Direct coupling of the piezoelectric body to an adequate relay circuit may also actuate the alarm. Referring now to Fig. 6 there is shown another embodiment of this invention. A piezoelectric body 1 of a PVDF resin is provided with electrodes 2, 2¹ of conductive layer as terminals on both sides thereof according to any suitable process such as vapour deposition of metal film. The terminals are mounted upon the vibration body 4, when measuring is practised, by way of double-sided adhesive tape or an adhesive or by conventional securing means such as small screws or clamps. The terminals are connected by way of a FET circuit 8 to a relay circuit 9 which is, in turn, connected to an alarm 10 and actuates the alarm when a predetermined voltage level is attained. Various conventional means, for example a voltmeter, may be used as the relay circuit. The voltmeter employed herein is built into the circuit in such a way that the indicator thereof actuates the alarm when a predetermined voltage level is exceeded.

The vibrations of the vibration body 4 are transformed by way of the piezoelectric element PVDF resin and delivered through the FET circuit 8 to the voltmeter and changes of amplitude of the vibrations are detected by corresponding changes in the voltage. When abnormal vibrations are generated in the vibration body thereby to generate a voltage exceeding the predetermined level, the indicator of the voltmeter completes the circuit for the alarm which is thereby actuated.

EXAMPLE 1

A piece of mono-axially oriented PVDF film was provided with electrodes 2, 2¹ on both sides thereof by aluminium deposition, as shown in Fig. 2, and a static electric field of 500 KV/cm and heat were applied thereto to obtain a piezoelectric gauge element having a piezoelectric constant $d_{31}: 4.0 \times 10^7$ cgsesu.

A vibrometer pick-up shown in Fig. 2 was fabricated using said piezoelectric gauge element ($70 \times 10 \times 0.01$ mm³). The piezoelectric gauge element was attached to the vibration body 4 to be tested, made of aluminium sheet ($80 \times 12 \times 1$ mm³), by means of double sided adhesive tape 3.

One end of said aluminium sheet 4 was fixed and to the other end thereof were applied sinusoidal vibrations of from 10 Hz to 100 Hz using a vibrator, the vibrations were increased from 10 Hz to 100 Hz in steps of 10 Hz.

The voltage generated by the piezoelectric gauge element was subjected to impedance conversion through a FET and then measured using an oscilloscope. A wave form having the same frequency as that applied to the aluminium sheet was observed, and was found to follow that applied to the aluminium sheet with high accuracy. The frequency characteristics were flat. The amplitude of the vibrations in the aluminium sheet predetermined from the relation between the distortion and the output voltage in the pick-up always showed a constant value of 4.8 micron/cm irrespective of the changes in the frequency. The amplitude determined from the strain gauge provided for the reference in the vibrator was 5 micron/cm.

EXAMPLE 2

A mono-axially orientated PVDF film was provided with electrodes 2, 2¹ on both sides thereof by aluminium deposition and then there was applied thereto a static electric field of 500 KV/cm and heat to obtain a piezoelectric element of size $70 \times 10 \times 0.01$ mm³ and having a piezoelectric constant $d_{31}: 4.0 \times 10^{-7}$ cgsesu.

The piezoelectric element was secured at its one end to the stationary body 7 and secured at its other end to an aluminium sheet 4 which was, in turn, coupled to a vibrator. For the adhesives 3, 3¹, double sided adhesive tape was used.

A vibrator was operated to produce sinusoidal vibrations of from 1 Hz to 100 Hz and the voltage generated by the piezoelectric element was passed through the FET circuit 8 for the impedance conversion and then detected by the oscilloscope 6. High output voltage per unit displacement (quantity of displacement/length in piezoelectric body; micron/cm) of 0.016 mV is obtained. The frequency characteristics up to said 100 Hz were flat and the follow up characteristics for the changes in the frequency were extremely sharp.

WHAT WE CLAIM IS:—

1. A method of detecting or measuring vibration which comprises forming an electric circuit including as a piezoelectric element electrodes having therebetween a piezo-

It can also actuate an alarm employed in combination with a relay circuit. More specifically, a piezoelectric body of a PVDF resin is partially or entirely coupled to the vibration body to thereby transform the changes in the vibrations into a varying voltage. If a predetermined voltage level is exceeded by the generation of abnormal vibrations or the like, the alarm connected to said piezoelectric body is actuated to warn of the abnormal vibrations in the vibration body. For the above construction, the FET circuit is provided between said piezoelectric body and the relay circuit for the actuation of the alarm in order to alter the impedance so that the relay circuit connected to the alarm may be operated by the voltage produced in the piezoelectric body.

Direct coupling of the piezoelectric body to an adequate relay circuit may also actuate the alarm. Referring now to Fig. 6 there is shown another embodiment of this invention. A piezoelectric body 1 of a PVDF resin is provided with electrodes 2, 2¹ of conductive layer as terminals on both sides thereof according to any suitable process such as vapour deposition of metal film. The terminals are mounted upon the vibration body 4, when measuring is practised, by way of double-sided adhesive tape or an adhesive or by conventional securing means such as small screws or clamps. The terminals are connected by way of a FET circuit 8 to a relay circuit 9 which is, in turn, connected to an alarm 10 and actuates the alarm when a predetermined voltage level is attained. Various conventional means, for example a voltmeter, may be used as the relay circuit. The voltmeter employed herein is built into the circuit in such a way that the indicator thereof actuates the alarm when a predetermined voltage level is exceeded.

The vibrations of the vibration body 4 are transformed by way of the piezoelectric element PVDF resin and delivered through the FET circuit 8 to the voltmeter and changes of amplitude of the vibrations are detected by corresponding changes in the voltage. When abnormal vibrations are generated in the vibration body thereby to generate a voltage exceeding the predetermined level, the indicator of the voltmeter completes the circuit for the alarm which is thereby actuated.

EXAMPLE 1

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The voltage generated by the piezoelectric gauge element was subjected to impedance conversion through a FET and then measured using an oscilloscope. A wave form having the same frequency as that applied to the aluminium sheet was observed, and was found to follow that applied to the aluminium sheet with high accuracy. The frequency characteristics were flat. The amplitude of the vibrations in the aluminium sheet predetermined from the relation between the distortion and the output voltage in the pick-up always showed a constant value of 4.8 micron/cm irrespective of the changes in the frequency. The amplitude determined from the strain gauge provided for the reference in the vibrator was 5 micron/cm.

EXAMPLE 2

A mono-axially orientated PVDF film was provided with electrodes 2, 2¹ on both sides thereof by aluminium deposition and then there was applied thereto a static electric field of 500 KV/cm and heat to obtain a piezoelectric element of size $70 \times 10 \times 0.01$ mm³ and having a piezoelectric constant $d_{31}: 4.0 \times 10^{-7}$ cgsesu.

The piezoelectric element was secured at its one end to the stationary body 7 and secured at its other end to an aluminium sheet 4 which was, in turn, coupled to a vibrator. For the adhesives 3, 3¹, double sided adhesive tape was used.

A vibrator was operated to produce sinusoidal vibrations of from 1 Hz to 100 Hz and the voltage generated by the piezoelectric element was passed through the FET circuit 8 for the impedance conversion and then detected by the oscilloscope 6. High output voltage per unit displacement (quantity of displacement/length in piezoelectric body; micron/cm) of 0.016 mV is obtained. The frequency characteristics up to said 100 Hz were flat and the follow up characteristics for the changes in the frequency were extremely sharp.

WHAT WE CLAIM IS:—

1. A method of detecting or measuring vibration which comprises forming an electric circuit including as a piezoelectric element electrodes having therebetween a piezo-



electric material of a polyvinylidene fluoride resin, coupling said piezoelectric element at least partially to a vibration body, the vibration of which is to be detected or measured, and detecting or measuring the mechanical vibrations as changes in electrical charge or in voltage emitted by said piezoelectric material.

2. A method according to Claim 1, in which one end of the piezoelectric material is secured to a stationary body and the other end thereof is secured to said vibration body.

3. A method according to Claim 1 or 2, wherein the piezoelectric material has a linear elastic coefficient of not more than 5×10^{10} dynes per cm^2 .

4. A method according to any preceding claim, wherein the piezoelectric material has a thickness between the electrodes of not more than 100 microns.

5. A method according to any preceding claim, wherein the piezoelectric material comprises a copolymer of polyvinylidene fluoride.

6. A method according to any preceding claim, in which said piezoelectric element is coupled to the vibration body by means of double sided adhesive tape.

7. A method according to any of Claims 1 to 4, wherein the piezoelectric element is coupled to the vibration body by means of an adhesive.

8. A method according to any of Claims 1 to 6, wherein screws or clamps are used to couple the piezoelectric element to the vibration body.

9. A method according to any preceding claim, wherein the piezoelectric material is electrically polarized by the application of heat and a static electric field.

10. A method of detecting or measuring vibration, substantially as hereinbefore described with reference to any of Figs. 2 to 6 of the accompanying drawings.

11. A piezoelectric apparatus for detecting or measuring vibration, which comprises a piezoelectric element including a piezoelectric material of a polyvinylidene fluoride resin disposed between two electrodes, a detector means for detecting a voltage variation between said electrodes and means for securing the piezoelectric element to a vibration body, the vibration of which is to be detected or measured.

12. Apparatus according to Claim 11, wherein the piezoelectric material is connected *viz* the said electrodes and a field effect

transistor to a detecting or measuring device.

13. Apparatus according to Claim 11, which further includes a relay circuit and an alarm device actuable by the relay circuit and the relay circuit being actuable in accordance with a predetermined change in voltage emitted by the piezoelectric element.

14. Apparatus as claimed in any of Claims 11 to 13, in which said piezoelectric element having electrodes thereon is provided with pressure-sensitive adhesive means for securing it to a vibration body, the vibration of which is to be detected or measured.

15. Apparatus according to any one of Claims 11 to 14, wherein the piezoelectric material has a linear elastic coefficient of not more than 5×10^{10} dynes per cm^2 .

16. Apparatus according to any of Claims 11 to 15, wherein the piezoelectric material is a PVDF film of a beta-type crystal structure.

17. Apparatus according to any one of Claims 11 to 16, wherein the piezoelectric material is monoaxially orientated and has a piezoelectric constant d_{31} (as hereinbefore defined) of from 1×10^{-7} to 2×10^{-6} cgsesu.

18. Apparatus according to any one of Claims 11 to 16, wherein the piezoelectric material either is non-orientated or is biaxially orientated and has a piezoelectric constant d_{31} (as hereinbefore defined) of more than 1×10^{-7} cgsesu.

19. Apparatus according to any one of Claims 11 to 18, wherein the piezoelectric material has been electrically polarized by the application of heat and a static electric field.

20. Apparatus for detecting or measuring vibration, substantially as hereinbefore particularly described with reference to any of Figs. 2 to 6 of the accompanying drawings or with reference to the foregoing Example 1 or 2.

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