



(12) **EUROPEAN PATENT APPLICATION**

(21) Application number : **95300269.8**

(51) Int. Cl.⁶ : **B06B 1/06**

(22) Date of filing : **17.01.95**

(30) Priority : **25.02.94 JP 51086/94**

(43) Date of publication of application :
30.08.95 Bulletin 95/35

(84) Designated Contracting States :
BE DE FR GB

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(54) **Wave-receiving piezoelectric device.**

(57) A wave-receiving piezoelectric device is constituted by providing a tubular piezoelectric element including a piezoelectric body which has an outer surface and an inner surface constituting principal two surfaces, two opposite sides almost perpendicular to the two surfaces, a sectional shape corresponding to the thickness of a closed loop or a vortex, and an overall shape of roughly a tube, the piezoelectric body being polarized thicknesswise; and electrodes respectively disposed on the two surfaces; and by sandwiching the piezoelectric body at the two opposite sides with a pair of rigid members; so that an acoustic pressure received by outer surfaces of the rigid members is concentratively applied as a stress for changing a distance between the two opposite sides of the piezoelectric body. As a result, the piezoelectric device is provided with a remarkably increased hydrostatic piezoelectric constant (d_h) through selective enhancement of the contribution of axial deformation stress (d_{31} or d_{32} stress) than the piezoelectric body is used in an ordinary manner.

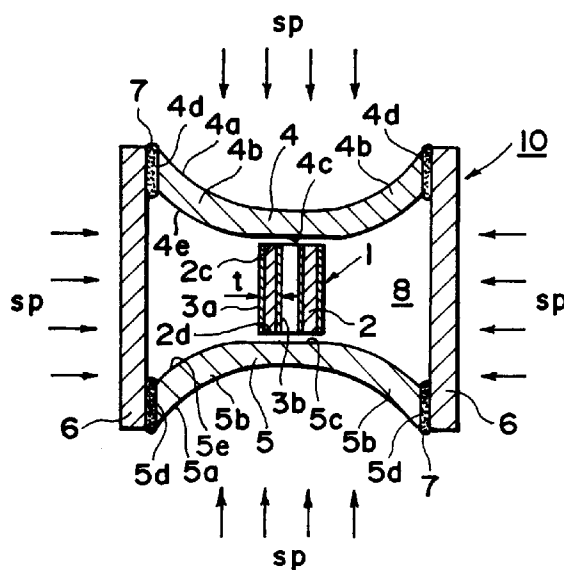


FIG. 1B

The present invention relates to a wave-receiving (or passive) piezoelectric device having an enhanced sensitivity of receiving an acoustic wave.

There have been known wave-receiving piezoelectric devices inclusive of a microphone which is generally placed in a gaseous medium such as air or a gas so as to receive an acoustic wave propagated through the gaseous medium, and a hydrophone which is generally placed in a liquid medium such as water or other liquids so as to receive an acoustic wave propagated through the liquid medium.

The acoustic wave-receiving sensitivity of such a piezoelectric device may be expressed in terms of a hydrostatic piezoelectric constant d_h in case where the device has a sufficiently smaller size than the wavelength of the acoustic wave, and is of course better if the d_h constant is larger.

Generally, a piezoelectric material or body has a d_h constant, which is given as a total of a component in the direction of polarization (d_{33}) and components in two directions perpendicular to the polarization direction (d_{31} and d_{32}) according to the following equation:

$$d_h = d_{31} + d_{32} + d_{33}.$$

In a sheet-form piezoelectric body generally used in the art, the polarization direction is frequently taken in the thickness direction in view of the facility of polarization treatment, and the component (d_{33}) in the thickness direction and the components (d_{31} and d_{32}) in the two directions perpendicular thereto have mutually opposite signs, i.e., mutually contradictory functions, in many cases.

Taking note of such characteristics of a sheet-form piezoelectric body, there has been proposed a device structure wherein a function of an acoustic pressure acting onto sides of a sheet-form piezoelectric body is excluded by a frame member to remove the contribution of d_{31} and d_{32} components and preferentially take out the contribution of d_{33} component, thereby consequently providing an increased d_h constant (Japanese Laid-Open Patent Application (JP-A) 62-220099). In such an instance, it has been also found according to our study that, when a sheet-form piezoelectric body is sandwiched between a pair of rigid members having a larger area, it is possible to obtain a piezoelectric device showing an apparent d_h constant which exceeds the d_{33} constant of the sheet-form piezoelectric body, respectively relative to the acoustic pressure acting thereon, depending on an areal ratio (pressure-amplifying ratio) between the pair of rigid members and the sheet-form piezoelectric body.

However, in such a piezoelectric device principally utilizing a piezoelectric constant d_{33} in the thickness direction of a sheet-form piezoelectric body as described above, particularly one having a structure comprising a sheet-form piezoelectric body having electrodes on both surfaces thereof and a pair of rigid

members having a larger area and sandwiching the both surfaces of the sheet-form piezoelectric body via the electrodes, it is necessary to narrow the electrode area in order to obtain an increased pressure-amplifying ratio by using rigid members having a definite area. As a result, it becomes difficult to take out lead wires from the electrodes, and the capacitance of the piezoelectric device becomes smaller, thus resulting in an increased internal impedance. Thus, a detection circuit for taking out a voltage output from such a device is required of an input impedance which is still larger than the internal impedance of the device. Accordingly, the detection circuit suffers from disadvantages such that it is liable to be affected by noises of, e.g., electromagnetic wave, its performances are liable to be unstable, it cannot use long lead wires, and it should be constituted while paying special measures against such problems.

An object of the present invention is to realize a wave-receiving piezoelectric device having a higher sensitivity from a given piezoelectric material or body, while obviating difficulties in device structure including a detection circuit encountered in a piezoelectric device utilizing a d_{33} constant of a sheet-form piezoelectric body as described above.

According to our study, in order to accomplish the above object, it has been found effective to constitute a device structure using a piezoelectric body polarized, e.g., in its thickness direction, wherein, rather than its d_{33} component, d_{31} and d_{32} components in directions perpendicular thereto are positively utilized, particularly to constitute such a device structure by using a piezoelectric body in the form of a generally hollow tube.

More specifically, according to the present invention, there is provided a wave-receiving piezoelectric device, comprising:

a tubular piezoelectric element including a piezoelectric body which has an outer surface and an inner surface constituting principal two surfaces, two opposite sides almost perpendicular to the two surfaces, a sectional shape corresponding to the thickness of a closed loop or a vortex, and an overall shape of roughly a tube, the piezoelectric body being polarized in its thickness direction; and electrodes respectively disposed on the two surfaces; and

a pair of rigid members sandwiching the piezoelectric body at the two opposite sides; so that an acoustic pressure received by outer surfaces of the rigid members is concentratively applied as a stress for changing a distance between said two opposite sides of the piezoelectric body.

In order that an acoustic wave is concentrated as a stress for changing the distance between the opposite sides of a generally tubular piezoelectric body as described above, it is preferred that the pair of rigid members are displaceable in response to the acoustic pressure without hindering the displacement of the

tubular piezoelectric body in the axial direction thereof, and the rigid members are disposed so as to substantially interrupt the acoustic pressure from acting on at least one of the inner and outer surfaces of the tubular piezoelectric body. It is particularly preferred that the outwardly projecting portions not used for sandwiching the tubular piezoelectric body of the pair of rigid members are caused to define an airtight space with their inner surfaces.

In the present invention, the outer surface (effective action area) of a rigid member which is effective to receive an acoustic pressure to be concentrated as a stress for causing a deformation of the piezoelectric body in its surface extension direction, i.e., an axial direction, is not an outer surface area per se in an ordinary sense but is the projection area of the rigid member onto a plane perpendicular to the pressing direction in which the rigid member presses the piezoelectric body and more exactly a difference obtained by subtracting, from the projection area, the area of an inner surface opposite to the outer surface of the rigid member (more exactly, the projection area thereof onto a plane perpendicular to the pressing direction, similarly as above) in case where the acoustic pressure also acts on the inner surface. In the case of a tubular piezoelectric body, the above-mentioned "plane perpendicular to a direction of pressing the piezoelectric body" is generally regarded as a plane parallel to the sides of the piezoelectric body, i.e., a plane perpendicular to the axis of the tubular piezoelectric body.

Further, the acoustic wave referred to herein should be construed as a wave of pressure oscillation and not limited to the audio frequency wave. More exactly, the acoustic wave used herein means a wave of pressure oscillation having a wavelength which is comparable to or larger than the length of the rigid member. The acoustic pressure is the pressure of the oscillation mentioned above.

As described above, according to the present invention, it is possible to obtain an apparently remarkable increase in d_h constant of a tubular piezoelectric body by sandwiching two sides of the tubular piezoelectric body having a definite area with a pair of rigid members having a larger area, thereby increasing the effective action area for acoustic pressure of the tubular piezoelectric body contributing to the deformation of the tubular piezoelectric body in its axial direction. Further, by changing the length in axial direction of the tubular piezoelectric body independently of a pressure-amplifying ratio determined by a ratio of the effective action area of the rigid member/the side area of the tubular piezoelectric body, it is possible to change the electrode area of the device, whereby the internal impedance of the device can be arbitrarily set. The interruption of an acoustic pressure from acting onto the inner surface of the rigid member performed for pressure amplification by the rigid member

also has an effect of interrupting the contribution of a component in thickness direction (d_{33} component) which, in many cases, has a function adverse to the effective components (d_{31} and d_{32} components of a piezoelectric body polarized in the thickness direction) perpendicular to the polarization directions of the piezoelectric body among the components of the d_h constant, i.e., an effect of shielding the action of the acoustic pressure onto the piezoelectric body in the thickness direction. This also contributes to an apparent increase in d_h constant.

These and other objects, features and advantages of the present invention will become more apparent upon a consideration of the following description of the preferred embodiments of the present invention taken in conjunction with the accompanying drawings, wherein like reference numerals are used to denote like parts.

Figures 1A and 1B are a partially cut-out perspective view and a front sectional view, respectively, of an embodiment of the wave-receiving piezoelectric device of the invention.

Figures 2A and 2B are an enlarged plan view and an enlarged front sectional view, respectively, of a tubular piezoelectric element contained in the embodiment shown in Figures 1A and 1B.

Figures 3 and 4 are respectively a front sectional view of another embodiment of the wave-receiving piezoelectric device of the invention.

Figure 5 is a schematic sectional view of an example of a sheet-form polymeric piezoelectric element before shaping into a tubular piezoelectric element.

Figures 6A and 6B are a plan view and a front view, respectively, of a tubular piezoelectric element shaped from the sheet-form piezoelectric element shown in Figure 5.

Figure 7 is a schematic sectional view of another example of a sheet-form polymeric piezoelectric element before shaping into a tubular piezoelectric element.

Figures 8A and 8B are a plan view and a front view, respectively, of a tubular vortex-form piezoelectric element shaped from the sheet-form piezoelectric element shown in Figure 5 or 7.

Figure 9 is a sectional view of a mold used for shaping into a tubular piezoelectric element having a vortex section in an Example.

Figure 1A is a partially cut-out perspective view of an embodiment of the wave-receiving piezoelectric device (hereinafter simply called "piezoelectric device") according to the present invention, and Figure 1B is a corresponding front sectional view. Further, Figures 2A and 2B are an enlarged plan view and an enlarged front sectional view, respectively, of a tubular piezoelectric element contained in the embodiment. Referring to these figures, a piezoelectric device 10 comprises a tubular piezoelectric element 1

which in turn comprises a piezoelectric body 2. The piezoelectric body 2 has an outer surface 2a and an inner surface 2b constituting two principal surfaces sandwiching a thickness t , also has mutually opposite two sides 2c and 2d (shown as upper and lower faces in the figures) perpendicular to the two surfaces 2a and 2b, has a sectional shape corresponding to the thickness of a closed loop (an annular shape in this embodiment), has an overall shape of roughly a tube, and has a polarization p in the thickness direction. The tubular piezoelectric element 1 further comprises an electrode 3a and an electrode 3b respectively formed on the two surfaces 2a and 2b of the piezoelectric body 2. In addition to the piezoelectric element 1, the piezoelectric device 10 further includes a pair of rigid members 4 and 5 sandwiching the tubular piezoelectric body 2 at its opposite two sides 2c and 2d and having a larger area than the sides, so that an acoustic pressure sp acting on the pair of rigid members 4 and 5 is concentratively applied as a stress for changing (reducing) the distance between the opposite two sides 2c and 2d of the tubular piezoelectric body 2.

In this embodiment, the tubular piezoelectric body is sandwiched at its opposite two sides 2c and 2d with the pair of rigid members 4 and 5 each having the shape of a bowl having a horizontal shape of a circle. The rigid members 4 and 5 are respectively disposed to have curved outer surfaces 4a and 5a and outwardly extending portions 4b and 5b not participating in sandwiching the piezoelectric body 2. The rigid members 4 and 5 are further formed to have flat pressing faces (bottom faces) 4c and 5c so that the faces 4c and 5c are uniformly abutted and bonded, if necessary, to the flat sides 2c and 2d of the tubular piezoelectric body 2. Further, the pair of rigid members 4 and 5 sandwiching the tubular piezoelectric body 2 (and accordingly the tubular piezoelectric element 1 including it) is accommodated within a rigid cylinder 6 so that gaps between their sides 4d and 5d and the cylinder 6 are sealed with an elastomer resin 7.

In this embodiment, the pair of rigid members 4 and 5 receive from upper and lower directions an acoustic pressure sp corresponding to their effective action area (i.e., not that of the curving outer surfaces 4a and 5a per se but the area of projection of the outer surfaces onto a horizontal plane parallel to the sides 2c and 2d of the tubular piezoelectric body 2), and the acoustic pressure is concentrated onto the sides having a smaller area of the tubular piezoelectric body 2. The ratio of the effective action area to the area of the side of the tubular piezoelectric body corresponds to a pressure-amplifying ratio.

The elastomer resin 7 in this embodiment is used to keep an inner space 8 defined by the inner faces 4e and 5e of the pair of rigid members 4 and the inner face of the rigid cylinder 6 as an airtight space shield-

ed from the direct action of an acoustic pressure sp while not hindering the displacement (movement) of the pair of rigid members 4 and 5 for causing a size change of the tubular piezoelectric body 2 in its axial direction. As a result, the pressure within the inner space 8 defined by the rigid members 4 and 5 having a rigidity sufficient to suppress the deformation thereof by an acoustic pressure and the similarly rigid cylinder 6 is held substantially constant, and the acoustic pressure is substantially prevented from acting onto the inner faces 4e and 5e of the outwardly extending portions of the rigid members and also in directions for causing changes in peripheral size and thickness t of the piezoelectric element 1 contributing to d_{33} constant of the piezoelectric element 1. In order to enhance or control the acoustic pressure-interrupting function of the inner space 8, it is possible to establish a reduced pressure within the inner space or fill the space with an arbitrary gas or an arbitrary cushioning material, such as a foam resin.

Figure 3 is a front sectional view of a wave-receiving piezoelectric device 20 according to another embodiment of the present invention. A tubular piezoelectric element 1 used in the piezoelectric device 20 is similar to the one in the embodiment of Figures 1A and 1B but is used together with different shapes of rigid members 14 and 15, i.e., rigid plates 14 and 15 each having a sectional shape of generally "U" and having projecting faces 14f and 15f, respectively, at their peripheries. Corresponding to the rigid members 4 and 5, the rigid plates 14 and 15 as rigid members of the present invention have outer surfaces 14a and 15a, projecting portions 14b and 15b, pressing faces 14c and 15c, sides 14d and 15d, and projecting inner faces 14e and 15e, respectively. Further, a gap between the inner faces 14f and 15f projecting in the form of "U" of the rigid plates 14 and 15 is sealed with an elastomer resin 17 so that the rigid plates are displaceable in the direction of axis of the tubular piezoelectric body 2 in response to an acoustic pressure. Similarly as in the previous embodiment, an inner space 18 thus formed can be filled with, e.g., a gas or a foam resin, or can be made vacuum. Incidentally, a material having a compression deformability larger than that of the piezoelectric body 2 can be used in place of the elastomer resin 17 for sealing the gap or a foam resin filling the inner space 18.

Also in the embodiment of Figure 3, the piezoelectric body 2 is selectively pressed in the direction perpendicular to the sides thereof (i.e., the axial direction of the tubular piezoelectric body 2), and an acoustic pressure is prevented from acting on the whole region of the inner faces 14e and 15e opposite to the outer surfaces 14a and 15a of the plates 14 and 15. Accordingly, the whole area of the outer surfaces 14a and 15a can be utilized as an effective action area.

In order to join a pair of rigid members at peripheral parts and seal a gap therebetween, it is also possible to use a member having both rigidity and elasticity, such as a bellows or a plate spring instead of filling with an elastomer resin 17 as in this embodiment.

Figure 4 is a front sectional view of a piezoelectric device 30 according to another embodiment of the present invention. The piezoelectric device 30 also includes a tubular piezoelectric element 1 similar to the one used in the embodiment of Figures 1A and 1B and shown in Figures 2A and 2B. The rigid members used in this embodiment are a pair of flat rigid plates 24 and 25, and the pressing faces 24e and 25e thereof are abutted to and preferably also bonded to a pair of sides 2c and 2d (shown as upper and lower faces in Figure 4) of the tubular piezoelectric body 2 to make an inner space 2e of the tubular piezoelectric body 2 airtight. As a result, the inner faces of the rigid members including the pressing faces 24e and 25e do not receive the action of an acoustic pressure, and the whole area of the outer surfaces 24a and 25a can be used as an effective action area for the acoustic pressure and provides a pressure-amplifying ratio corresponding to a ratio thereof to a smaller area of the faces 2c and 2d to be pressed of the tubular piezoelectric body 2. The piezoelectric element 30 of this embodiment is simple in structure but does not cause a so much increase in effective action area as in the piezoelectric device of Figure 1 or Figure 2, thus being unable to expect an effective pressure amplification. Further, according to this embodiment, it is impossible to suppress the adverse contribution of d_{33} constant due to an acoustic pressure p acting onto the outer peripheral surface of the piezoelectric body 2 of diminishing the output based on the d_{31} or d_{32} constant intended by the present invention. These are disadvantages of this embodiment.

A tubular piezoelectric element 1 comprising a hollow tubular piezoelectric body 2, which is a ceramic one, having a polarization p in its thickness direction, and electrodes 3a and 3b on both surfaces of the piezoelectric body 2, as shown in Figure 2 and used in the above-described embodiments, is also commercially available (e.g., a cylindrical PZT piezoelectric element available from K.K. Tokin) and is suitably used in the present invention. On the other hand, in the case of a polymeric piezoelectric element, a film or sheet-form piezoelectric element as shown in Figure 5 (a thicknesswise polarized piezoelectric element) comprising a polymeric piezoelectric film 12 and electrodes 13a and 13b on both surfaces thereof may be wound around an axis by utilizing its flexibility and the opposite ends of the film may be bonded to each other with an epoxy resin 27, etc., to form a polymeric piezoelectric element 11 as shown in Figures 6A (plan view) and 6B (front view), which functions similarly as a piezoelectric element 1 of a ceramic type as shown in Figure 2. It is desired to fix the tub-

ular shape by thermal fixation, as desired, after the winding.

Preferred examples of the polymeric piezoelectric material used in the present invention may include vinylidene cyanide-vinyl acetate copolymer having a relatively high heat-resistance and vinylidene fluoride resin-based piezoelectric materials having excellent piezoelectric characteristics. Particularly, compared with vinylidene fluoride (VDF) homopolymer requiring a uniaxial stretching treatment for β -form crystallization exhibiting piezoelectricity, it is preferred to use VDF copolymers (e.g., copolymers of a major amount of VDF and a minor amount of trifluoroethylene (TrFE) or tetrafluoroethylene (TFE)) capable of β -form crystallization under ordinary crystallization conditions. The most preferred example is a copolymer of a major amount (particularly, 70 - 80 mol. %) of VDF and a minor amount (particularly 30 - 20 mol. %) of TrFE.

Such a polymeric piezoelectric material may be formed into a film, e.g., by melt-extrusion, followed by uniaxial stretching or heat treatment below the softening temperature as desired, and polarization according to electric field application below the softening temperature, to provide a polymer piezoelectric material in the form of a film or sheet 12. The film or sheet of piezoelectric material may be used as a single layer or a laminate of 2 - 20 layers with identical polarization directions or alternately reverse polarization directions with an intermediate electrode layer between layers.

As is understood from the above embodiments, the rigid member used in the present invention having a function of concentrating an acoustic pressure received by an outer surface of a larger area onto the sides of a tubular piezoelectric body having a relatively small area can also be regarded as an acoustic pressure amplifier. In this instance, a measure of the amplifying ratio is the above-defined areal ratio of the effective action area of the rigid member and the area of the sides (pressed faces) of the piezoelectric body. This ratio of course exceeds 1 and the upper limit thereof may be selected so that the stress (based on the amplified acoustic pressure) is suppressed within a range not causing a plastic deformation of the piezoelectric body.

As another aspect, in the piezoelectric device according to the present invention, an acoustic pressure received by the outer surfaces of a larger area of the rigid member is amplified and concentrated onto the sides of a smaller area of the tubular piezoelectric element. Accordingly, in order to attain an effective d_{31} or d_{32} amplifying output (attain an agreement between the pressure-amplifying ratio and an increase in piezoelectric characteristics (d_p constant)), it is necessary that the above-mentioned amplified and concentrated acoustic pressure is effectively converted into a stress causing a compression of the tub-

ular piezoelectric body in its planar (or axial) direction. In other words, it is desirable to suppress deformations, such as bending or swelling in the thickness or radial direction of the tubular piezoelectric element, increasing the contribution of d_{33} component to the minimum.

From this aspect, in the above-mentioned case of forming a tubular piezoelectric element 11 by winding a polymeric piezoelectric member 12, it is desired to provide an increased thickness t , if necessary, by adopting a laminated structure. Further, in order to suppress the thicknesswise or radial deformation of a tubular piezoelectric element comprising a polymeric piezoelectric material, it is preferred to use a piezoelectric element comprising a piezoelectric sheet onto the surface of which a perforated sheet electrode of a mesh or perforated sheet structure has been embedded so as to reinforce the polymeric piezoelectric sheet within an extent of retaining the flexibility thereof (as disclosed in Japanese Patent Applications Nos. 4-158844 and 4-203160), instead of using an ordinary polymeric piezoelectric element as shown in Figure 15 comprising a piezoelectric film or sheet 12 having vapor-deposited electrodes 13a and 13b on both surfaces thereof; and it is further preferred to wind a sheet-form piezoelectric element as shown in Figure 5 or Figure 7 in plural turns to form a piezoelectric element 21 which has a sectional (or planar) shape of a vortex and an overall shape of generally a tube as shown in Figures 8A (plan view) and 8B (front view).

The electrodes 3a, 3b, 13a and 13b (and 23a and 23b) can be vapor-deposited electrodes, foil electrodes applied with an adhesive or thermally sprayed metal electrodes (as disclosed in EP-A 0528279). It is however preferred to use electrodes ensuring a flexibility as a whole (1) so as not to hinder the compression deformation of the piezoelectric body in its planar extension direction due to an amplified acoustic pressure, and (2) so as to allow easy shaping into a tube or a vortex in the case of a polymeric piezoelectric body, e.g., vapor-deposited electrodes, electrodes formed by coating with an electroconductive paint, and the above-mentioned perforated sheet electrodes 23a and 23b.

The piezoelectric body used in the present invention always receives a compression deformation stress in its planar extension direction. Accordingly, it is also preferred that (3) the electrodes have a strong peel strength at the boundary with the piezoelectric body. In this sense, the above-mentioned perforated sheet electrodes, particularly the mesh electrodes, are preferred.

[Examples]

Hereinbelow, some Examples and Comparative Examples of a hydrophone as a specific embodiment

of the wave-receiving piezoelectric device according to the present invention are described.

Test pieces and hydrophones produced in the Examples and Comparative Examples were evaluated with respect to the hydrostatic piezoelectric constant (d_h constant) measured in the following manner.

A sample (device) was dipped in silicone oil contained in a pressure vessel, and the vessel was pressurized under a continuously increasing pressure P (Newton (N)/m²) from a nitrogen gas supply to measure a charge Q (Coulomb (C)) generated in the device. Then, a charge increment dQ corresponding to a pressure increment dP was measured in the neighborhood of a gauge pressure of 2 kg-f/cm², and the d_h constant was calculated by the following equation:

$$d_h = (dQ/dP)/A,$$

wherein A denotes the electrode area (m²), and d_h constant was obtained in the unit of C/N.

The d_{31} and d_{32} constants of a test piece were measured in the following manner.

An apparatus for measuring viscoelasticity and piezoelectricity ("Rheolograph Solid", mfd. by K.K. Toyo Seiki Seisakusho) was used, and a test piece was set at a clamp length of 18 mm in the longitudinal direction. One (fixed side) clamp was connected to a load cell and the other (moving side) clamp was connected to a vibrator of the measurement apparatus. A static load of 0.35 kg was put on the sample piece, and then a minute displacement vibration at a frequency of 0.8 Hz was applied thereto in superposition by the vibrator. Then, a variation ΔQ (C) in charge induced between the electrodes of the test piece and a variation ΔT (N/m²) in tension per unit sectional area exerted by the load cell were measured to effect a calculation based on the following equation:

$$d_{31} \text{ or } d_{32} = (\Delta Q/\Delta T)/A$$

whereby d_{31} and d_{32} was obtained in the unit of C/N.

Herein, a test piece for measurement was obtained by forming a 0.03 μ m-thick vapor-deposited aluminum electrode on both sides of a polymeric piezoelectric film, and cutting 5 mm-wide and 25 mm-long strips out of the coated piezoelectric film. The test piece strips were cut out in two types so that their longitudinal directions were parallel (d_{31} direction) or perpendicular (d_{32} direction), respectively, to the stretched direction (MD) of the piezoelectric film.

Comparative Example 1

A VDF (vinylidene fluoride) homopolymer ("KF#1000", mfd. by Kureha Kagaku Kogyo K.K.) was extruded at a die temperature of 265 °C into a sheet, which was then uniaxially stretched at a stretching ratio of ca. 4 at a sheet temperature of 80 - 120 °C and polarized by corona discharge under an electric field of 50 - 90 V/ μ m to obtain a 250 μ m-thick polymeric piezoelectric film. Test pieces prepared from the polymeric piezoelectric film showed piezoelectric con-

stants including $d_h = -11.5$ pC/N, $d_{31} = +16.6$ pC/N and $d_{32} = +1.5$ pC/N.

Then, an electroconductive nickel paint ("Shintron E-63", mfd. by K.K. Shinto Chemitron) was sprayed onto both surfaces of the polymeric piezoelectric film to form 30 to 40 μ m-thick electrodes, and the coated film was cut into a 20 mm-wide and 80 mm-long strip so that its width extended in the MD direction (d_{31} direction), thereby obtaining a strip-form piezoelectric element having a sectional structure as shown in Figure 5.

Separately, two mold halves 101a and 101b providing a cylindrical inner surface having an inner diameter of 16 mm as shown in Figure 9 were provided, and the above-prepared strip-form piezoelectric element was wound in its longitudinal direction into a form of a vortex to be placed in the mold halves 101a and 101b, which were then joined with each other with bolts inserted through holes 103. Both ends of the vortex-form piezoelectric element were left unfixed. The mold containing the piezoelectric element was then held in a drier at 70 °C for 24 hours to thermally fix the piezoelectric element, to obtain a vortex-form piezoelectric element (of an outer diameter on the order of 20 mm) having a height h (roll width) = 20 mm, and a sectional area (pressed area) = 20 mm² as shown in Figures 8A and 8B. It was confirmed that the inner surface and the outer surface of the vortex-form piezoelectric element did not contact each other. Then, lead wires were connected to both electrodes 13a and 13b with an electroconductive instantaneous adhesive ("Cyclon", mfd. by Atsugi Chuo Kenkyujo K.K.) to complete a tubular piezoelectric element 21. The tubular piezoelectric element 21 showed a d_h constant of -11.3 pC/N.

Example 1

Then, a piezoelectric device 10 as a hydrophone functionally equivalent to the one shown in Figure 1 (but including a piezoelectric element 21 as shown in Figure 8 instead of the piezoelectric element 1) was obtained in the following manner.

First of all, an adhesive was applied onto both ends in the axial direction of a tubular piezoelectric element 21 identical to the one prepared in the above Comparative Example 1. Then, the adhesive-coated ends of the tubular piezoelectric element 21 were sandwiched by and bonded to a pair of bowl-shaped rigid plates 4 and 5 having a horizontal sectional shape of a circle. Then, the bonded structure including the rigid plates 4 and 5 was placed within a vinyl chloride resin-made cylinder 6 having a length of 53 mm, an inner diameter of 80 mm and a thickness of 5 mm. Then, gaps between the rigid plates 4, 5 and the cylinder 6 were filled with a urethane rubber adhesive to fix them with each other and make the resultant inner space airtight, thereby obtaining a piezoelectric

device 10. Actually, the bowl-shaped rigid plates 4 and 5 were obtained by working plastic lens products of acrylic resin so as to provide flat pressing faces 4e and 5e. The thickness was 5 mm, and the sides 4d and 5d provided a horizontal sectional diameter of 75 mm (corresponding to a pressure-receiving area of 4420 mm²). Lead wires connected to the tubular piezoelectric element 21 were taken out separately through bores in the rigid plates 4 and 5, respectively, and the bores were then sealed. The piezoelectric device 10 showed a d_h constant of +1,160 pC/N.

Comparative Example 2

A polymeric piezoelectric film identical to the one used in Comparative Example 1, provided with identical electrodes and cut into a 20 mm-wide and a 140 mm-long strip, thus providing a sheet-form piezoelectric element having a sectional structure as shown in Figure 5. Then, the sheet-form piezoelectric element was subjected to a vortex-shaping operation similarly as in Comparative Example 1 to complete a tubular vortex-form piezoelectric element 21 having a height h = 20 mm, a sectional area (pressure-receiving area) = 35 mm² and an outer diameter of ca. 30 mm. The piezoelectric element 21 showed a d_h constant of -11.3 pC/N.

Example 2

A piezoelectric device 10 was prepared in the same manner as in Example 1 except for using a tubular piezoelectric element 21 identical to the one prepared in Comparative Example 2. The piezoelectric device 10 showed a d_h constant of +690 pC/N.

Comparative Example 3

A VDF/TrFE (75/25 mol ratio) copolymer (mfd. by Kureha Kagaku Kogyo K.K.) was extruded at a die temperature of 265 °C into a sheet, which was then subjected to a heat treatment at 125 °C for 13 hours and a polarization treatment under an electric field of 60 MV/m for a total of 1 hour including a hold time of 5 min. at 123 °C and the accompanying temperature-raising and -lowering time. As a result, a 500 μ m-thick polymeric piezoelectric film was obtained. Test pieces prepared from the polymeric piezoelectric film showed $d_h = -12.5$ pC/N, $d_{31} = +13.2$ pC/N and $d_{32} = +13.0$ pC/N.

Then, acetone at 30 °C was applied onto both surfaces of the polymeric piezoelectric film and, after standing for 30 sec., both surfaces were sandwiched by a pair of wire nets of phosphor bronze in 300 mesh (twill weave; opening size = 45 μ m, wire diameter = 40 μ m, opening rate = 27.8 %). The laminate was then held for 2 min. at a temperature of 90 °C and a pressure of 50 kg-f/cm² for pressure bonding to embed the wire electrodes at the surface layers of the polymeric

piezoelectric film. The thus treated piezoelectric film provided with electrodes was then cut into a width of 20 mm and a length of 140 mm to obtain a strip-form piezoelectric element having a sectional structure as shown in Figure 7.

Then, the strip-form piezoelectric element was subjected to a vortex-shaping operation similarly as in Comparative Example 1 to complete a tubular vortex-form piezoelectric element 21 having a height $h = 20$ mm, a sectional area (pressure-receiving area) = 35 mm and an outer diameter of ca. 30 mm. The piezoelectric element 21 showed a d_h constant of -12.1 pC/N.

Example 3

A piezoelectric device 10 was prepared in the same manner as in Example 1 except for using a tubular piezoelectric element 21 identical to the one prepared in Comparative Example 3. The piezoelectric device 10 showed a d_h constant of +630 pC/N.

Comparative Example 4

A tubular piezoelectric element 1 as shown in Figures 2A and 2B was prepared by connecting lead wires with an electroconductive instantaneous adhesive identical to the one used in Comparative Example 1 to an inner electrode and an outer electrode of a commercially available cylindrical PZT piezoelectric element (available from K.K. Tokin, a sectional area = 90 mm², $d_{33} = +302$ pC/N, $d_{31} = d_{32} = -133$ pC/N) having an inner diameter of 12.3 mm, an outer diameter of 16.3 mm and a length of 10 mm and polarized in the thickness direction. The tubular piezoelectric element 1 showed a d_h constant of +26.7 pC/N.

Example 4

Both ends in the axial direction of a tubular piezoelectric element 1 identical to the one prepared in Comparative Example 4 was sealed with a pair of acrylic resin disks (an outer diameter = 17 mm, a thickness = 2 mm and a pressure-receiving area = 209 mm²) by using an adhesive to form a piezoelectric element 30 as shown in Figure 4. The piezoelectric element 30 showed a d_h constant of -550 pC/N.

Example 5

A piezoelectric device 10 was prepared in a similar manner as in Example 1 except for using a tubular piezoelectric element 1 identical to the one prepared in Comparative Example 4 and a pair of rigid plates 4 and 5 identical to those used in Example 1. The piezoelectric device 10 showed a d_h constant of -6,480 pC/N.

The above experimental results show that a

wave-receiving piezoelectric device according to the present invention showed a piezoelectric constant as large as up to several hundred times that of a corresponding piezoelectric device in a blank form (not provided with rigid members). Further, the amplifying ratio of the piezoelectric constant showed a strong correlation with a so-called areal ratio. Accordingly, it is suggested that a further large amplifying ratio can be obtained by increasing the areal ratio while paying attention to a deformation in a width direction of a piezoelectric body.

Consequently, it will be well understood that, if rigid members are carefully designed and disposed so that a piezoelectric body can be deformed at a small force in the direction of planar extension of a piezoelectric body and the action of an acoustic pressure onto the major surfaces of the piezoelectric body, an acoustic pressure received by outer surfaces of a larger area of the rigid members can be effectively concentrated to the sides of the piezoelectric body, thereby providing a remarkably increased piezoelectric constant.

As described above, according to the present invention, there is provided a wave-receiving piezoelectric device having a remarkably enhanced sensitivity of receiving an acoustic wave and effective for a microphone, a hydrophone, etc., by providing a tubular piezoelectric body polarized in its thickness direction to have a certain d_h constant, and sandwiching both sides perpendicular to the axis of the tubular piezoelectric body with a pair of rigid members of a larger area to provide an increased effective action area for receiving an acoustic pressure contributing to an axial deformation (d_{31} or d_{32} deformation) of the piezoelectric body, thereby causing a remarkable increase in apparent d_h constant without causing an increase in internal impedance.

Claims

1. A wave-receiving piezoelectric device, comprising:

a tubular piezoelectric element including a piezoelectric body which has an outer surface and an inner surface constituting principal two surfaces, two opposite sides almost perpendicular to the two surfaces, a sectional shape corresponding to the thickness of a closed loop or a vortex, and an overall shape of roughly a tube, the piezoelectric body being polarized in its thickness direction; and electrodes respectively disposed on the two surfaces; and

a pair of rigid members sandwiching the piezoelectric body at the two opposite sides; so that an acoustic pressure received by outer surfaces of the rigid members is concentratively applied as a stress for changing a distance between

said two opposite sides of the piezoelectric body.

2. A piezoelectric device according to Claim 1,
wherein said tubular piezoelectric element com-
prises a polymeric piezoelectric strip having prin-
cipal two surfaces sandwiching a thickness and
two sides almost perpendicular to the two surfac-
es and polarized in the thickness direction, and
has been obtained by winding the piezoelectric
strip together with electrodes respectively
formed on the two surfaces around a certain axis
into a shape of a tube or a vortex. 5 10

3. A piezoelectric device according to Claim 1,
wherein said tubular piezoelectric element com-
prises a tubular ceramic piezoelectric body hav-
ing an outer surface, and an inner surface consti-
tuting principal two surfaces sandwiching a thick-
ness and sides almost perpendicular to the two
surfaces, and electrodes respectively formed on
the two surfaces; said tubular ceramic piezoelec-
tric body being polarized in the thickness direc-
tion. 15 20

4. A piezoelectric device according to any of Claims
1 - 3, wherein said pair of rigid members respec-
tively have an outwardly projecting portion not
used for sandwiching the tubular piezoelectric
element, an inner surface of the outwardly pro-
jecting portion defining, in the piezoelectric de-
vice, an airtight space which is held in vacuum or
filled with a gas or a foam resin. 25 30

5. A piezoelectric device according to any of Claims
1 - 4, functioning as a hydrophone for receiving
an acoustic wave propagating through a liquid
medium. 35

6. A piezoelectric device according to any of Claims
1 - 4, functioning as a microphone for receiving
an acoustic wave propagating within a gaseous
medium. 40

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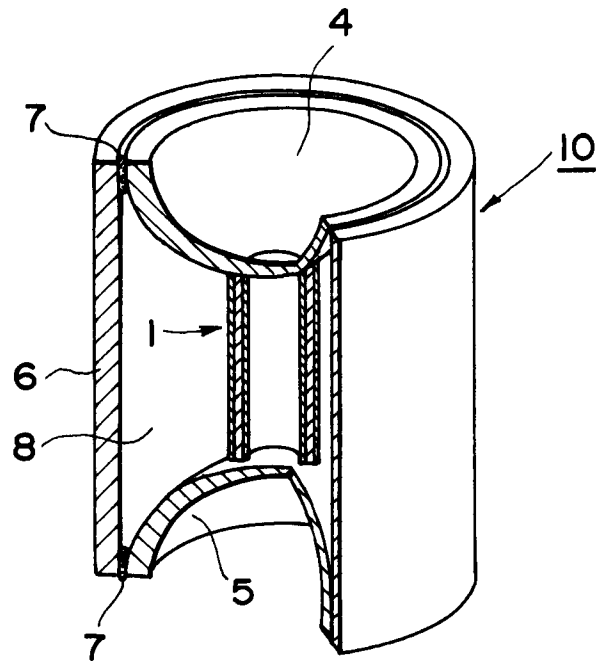


FIG. 1A

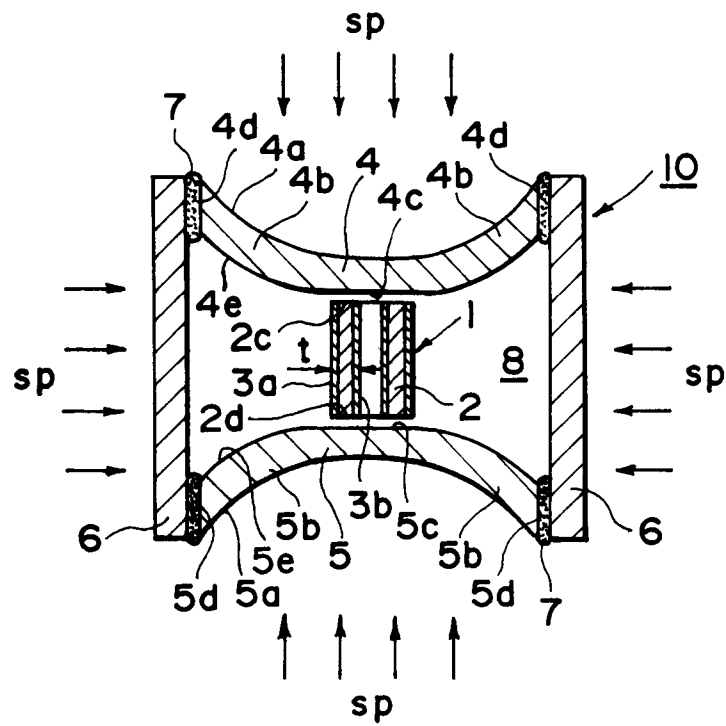


FIG. 1B

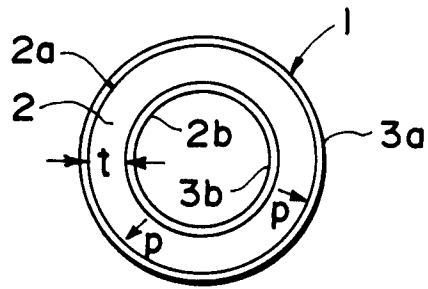


FIG. 2A

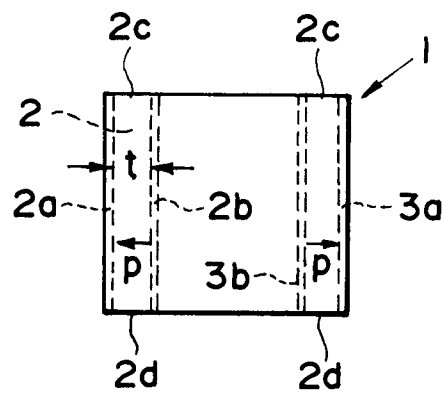


FIG. 2B

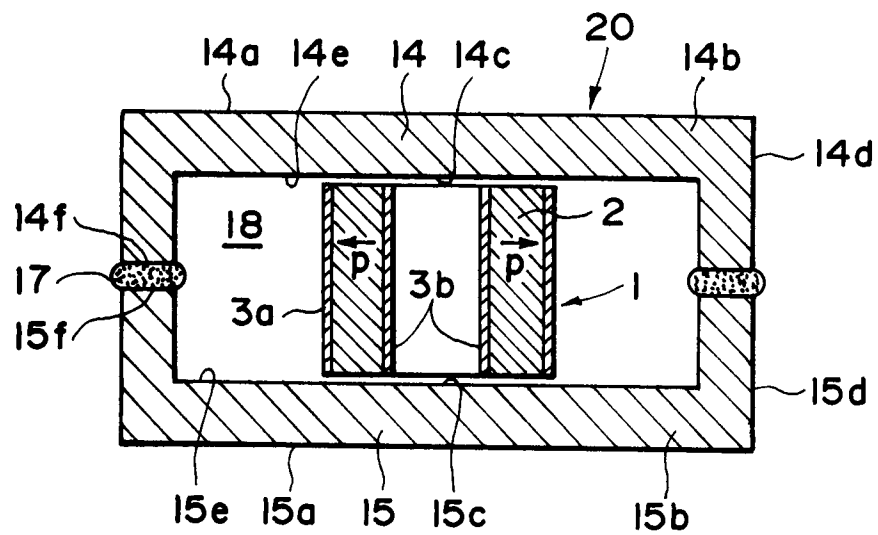


FIG. 3

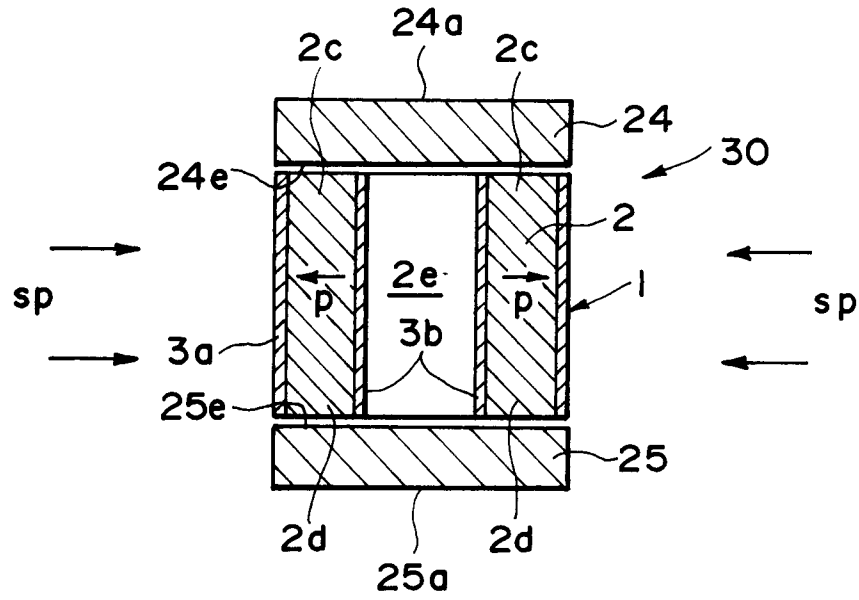


FIG. 4

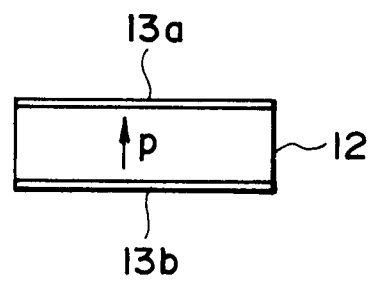


FIG. 5

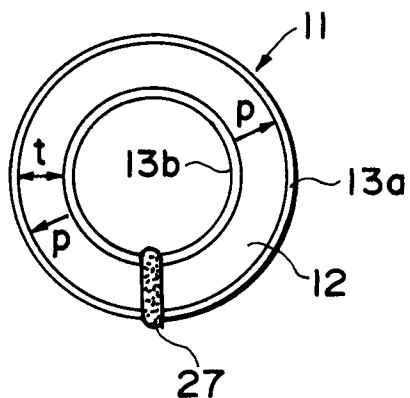


FIG. 6A

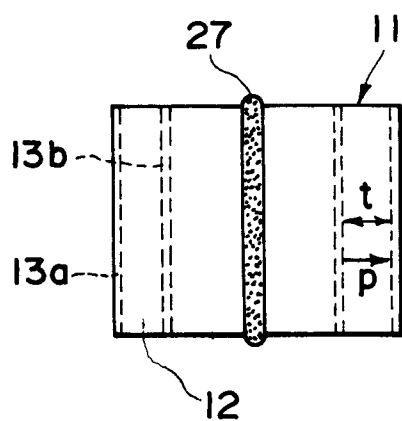


FIG. 6B

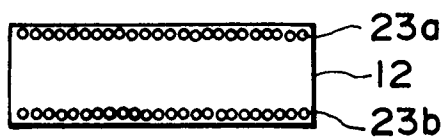


FIG. 7

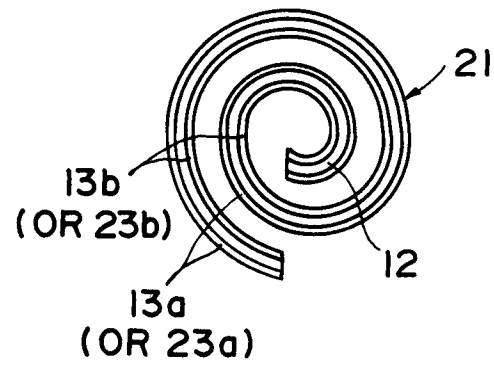


FIG. 8A

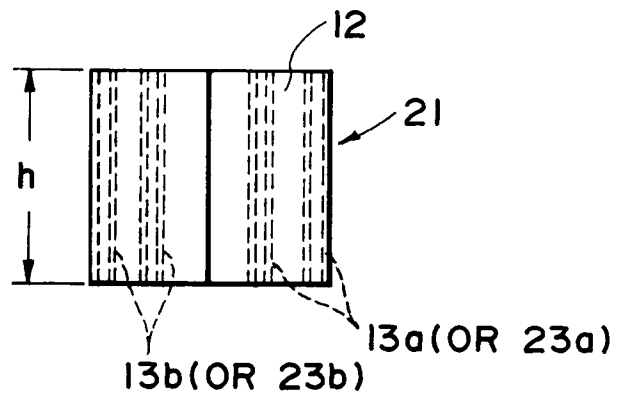


FIG. 8B

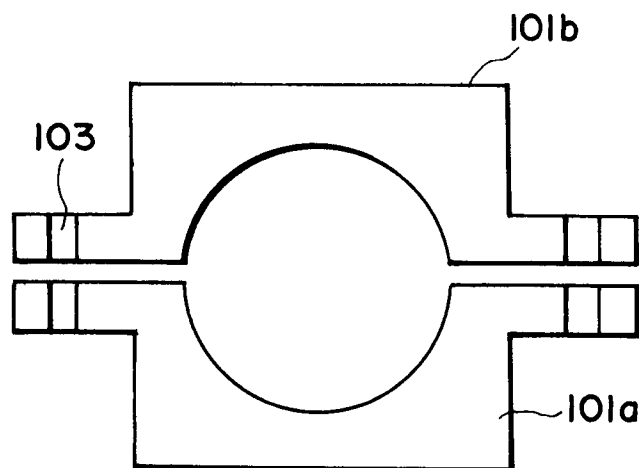


FIG. 9