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Epstein

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[54] ANNULAR 3M CLASS PIEZOELECTRIC CRYSTAL TRANSDUCER

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Related U.S. Application Data

[63] Continuation-in-part of Ser. No. 103,036, Dec. 31, 1970, abandoned.

[52] **U.S. Cl.** **310/9.5,** 252/62.9, 310/8.4, 310/9.6, 310/9.7

[51] **Int. Cl.** **H01v 7/02,** H04r 17/00

[58] **Field of Search** 310/8, 8.3, 8.4, 9, 9.5, 310/9.6; 252/62.9

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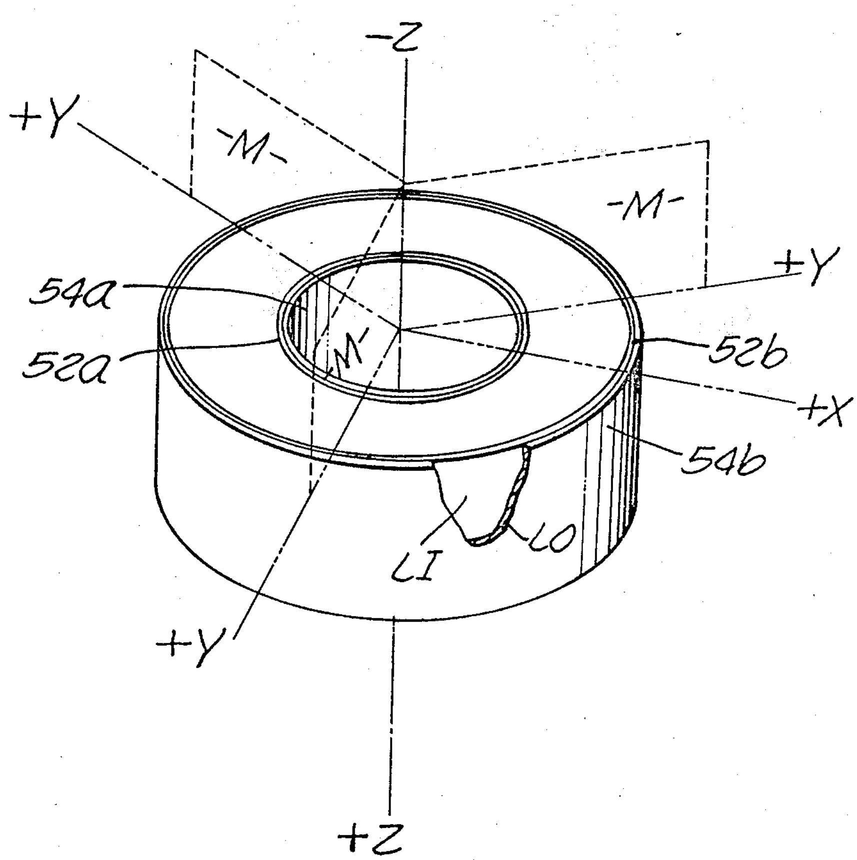
[57] **ABSTRACT**

The transducer of this invention utilizes an annular crystal of the 3m class operated in the shear mode with the shearing surfaces and the axis of the acceleration parallel to the Z axis of the crystal. When the crystal is composed of lithium niobate or lithium tantalate, the transducer has high efficiency and when the crystal is composed of lithium niobate it operates effectively over a very wide range of temperatures, including high temperatures above 1,000°F.

14 Claims, 3 Drawing Figures



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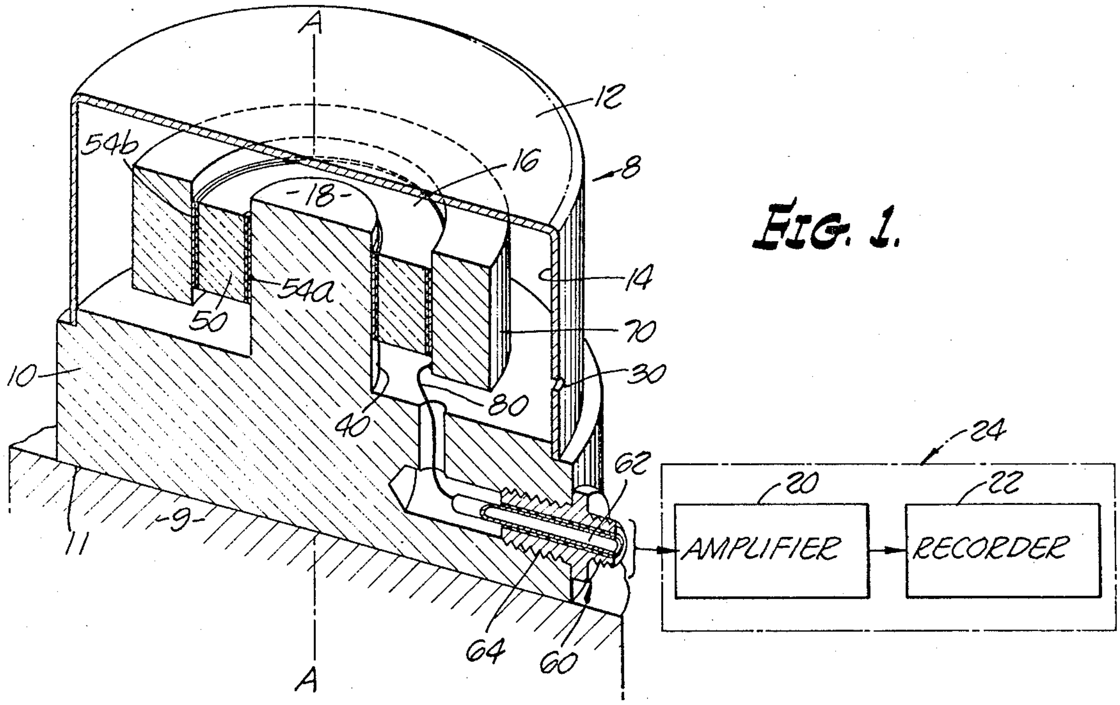

FIG. 1.

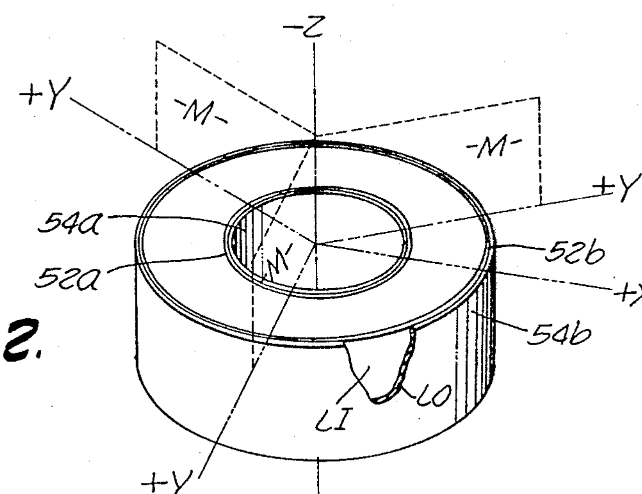

FIG. 2.

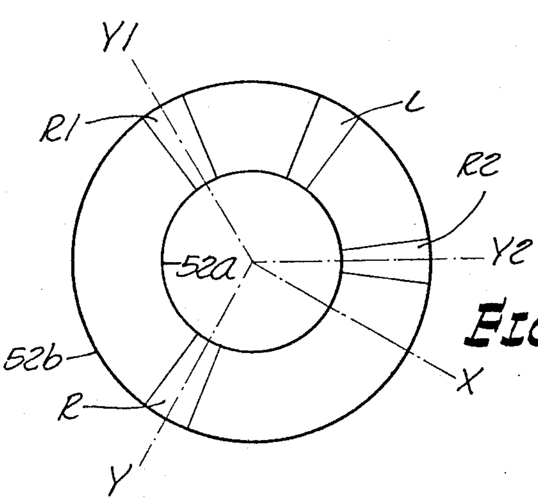

FIG. 3.

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ANNULAR 3M CLASS PIEZOELECTRIC CRYSTAL TRANSDUCER

This application is a continuation in part of copending application Ser. No. 103,036 filed Dec. 31, 1970 now abandoned.

CROSS REFERENCES TO RELATED APPLICATIONS

U.S. patent application Ser. No. 50,657, filed June 29, 1970, now Pat. No. 3,727,084 issued Apr. 10, 1973.

U.S. patent application Ser. No. 103,036, filed Dec. 31, 1970 now abandoned.

INTRODUCTION

This invention relates to electromechanical transducers and more particularly to an improved annular piezoelectric accelerometer free of any substantial pyroelectric effects and substantially free of a cross axis sensitivity. The invention also relates to such accelerometers which have high efficiency and is adapted to be operated over a wide range of temperatures including high temperatures above 1,000°F.

GENERAL DESCRIPTION OF THE INVENTION

The annular electromechanical tranducer of this invention makes use of a piezoelectric crystal of the 3m class cut to having an annular configuration with its cylindrical surfaces parallel to the Z axis. The accelerometer has electrodes on the cylindrical surfaces and is operated in shear mode with the shearing forces acting in a direction parallel to the Z axis. This arrangement makes optimum use of the characteristics of 3m crystal material when of annular configuration. The invention is applicable to all known 3m crystals, including lithium niobate, lithium tantalate, and natural tourmaline. Of these materials lithium niobate is particularly advantageous to employ because it has a high Curie temperature of about 1,200°C. Lithium niobate is also particularly advantageous to employ because it has the highest electromechanical coupling coefficient of the 3m crystalline materials known. For this reason, the invention will be described with reference to an annular accelerometer employing a crystal of the configuration described and composed of lithium niobate.

It is known that lithium niobate in monocrystalline form is piezoelectric and that its piezoelectric properties are preserved at high temperatures, such as at temperatures over 1,400°F., as well as at a low temperature, such as at temperatures of −60°F. The sensitivity of an accelerometer employing such a material depends in part on how the crystal is cut and how it is subjected to acceleration. The best embodiment of the invention now known makes use of a lithium niobate crystal of annular configuration operated in the shear mode with the axis of maximum sensitivity parallel to the Z axis. The electrodes are located on cylindrical surfaces parallel to the Z axis and the shearing forces are applied in directions parallel to the Z axis. This accelerometer not only has high sensitivity at high temperatures, but is also substantially free of cross-axis sensitivity. Furthermore, by taking special precautions, an accelerometer utilizing lithium niobate is provided for operating at such high temperatures over a long period of time.

This invention is particularly useful when employed as an accelerometer since the annular construction of the crystal of the best embodiment of this invention increases the stiffness of the crystal to better resist bending. This provides an accelerometer which has a high resonant frequency. Furthermore, the annular construction of the inertial mass supports the crystal as a unit even if the crystal becomes fractured. The accelerometer of this invention may be employed in detecting and measuring vibration and shock.

DRAWINGS

Various features of this invention are described below in connection with the accompanying drawings wherein:

FIG. 1 is an elevational view, partly in cross-section, of an annular accelerometer of one embodiment constructed in accordance with this invention;

FIG. 2 is a perspective view employed to explain the invention; and

FIG. 3 is a plan schematic view of the crystal employed in the invention.

DETAILED DESCRIPTION

Referring to FIG. 1 there is illustrated an accelerometer **8** comprising a housing formed partly by a base **10** and a case **12** providing a cylindrical hollow cavity **14** and comprising an annular acceleration sensing device **16** concentrically mounted on a post **18** projecting from the base **10** into the cavity **14.** The accelerometer **8** is rigidly secured to an object **9** undergoing test. The base **10** has a flat mounting surface **11** on its lower side, which surface is normal to the acceleration axis A—A and the Z axis of the crystal. The accelerometer is designed to have an axis A—A of maximum sensitivity parallel to the axis of the post **18** and perpendicular to the base **10.** This maximum-sensitivity axis A—A coincides with the optical or Z axis of the crystal as is apparent from comparing FIG. **1** with FIG. **2.** The accelerometer will be described as if mounted to detect the component of acceleration along a vertical axis.

The acceleration sensing unit **16** includes a piezoelectric crystal **50** that is electrically connected in such a manner that the electrical signals generated by the crystal **50** in response to such acceleration are combined to supply signals to a utilization device **24** in the form of a charge amplifier **20** and recorder **22.** These electrical signals are proportional to the acceleration of the object **9** in a direction parallel to the A—A axis. They are conventionally employed in the study of the vibratory motion of the object **9** on which the accelerometer **8** is mounted.

The post **18** may be formed unitary with the base **10** or it may be threadably or otherwise secured thereto or it may be fixed thereon by brazing. The casing or case **12** is firmly secured to the base **10** by a method such as by welding. The casing is provided with a small perforation or channel **30** to provide communication between the cavity **14** and the external atmosphere, for a purpose to be described hereinafter.

The post **18** is provided with a smooth circular cylindrical surface **40** that extends vertically parallel to the acceleration axis A—A. The acceleration sensing unit **16** comprises a piezoelectric crystal **50** and an inertial mass **70.** The crystal **50** is provided with two smooth parallel concentric circular cylindrical faces or surfaces **52***a* and **52***b* (FIG. **2**) which are coaxial with the Z axis of the crystal **50.** The surfaces *52a* and *52b* of the crystal **50** are coated with electrodes *54a* and *54b*. Each electrode is formed of a thin inner layer LI of conductive material, such as evaporated or sputtered chromium, and a thin outer layer LO of a non-corrosive, soft, malleable material, such as gold. One surface *52a* is in metallic contact with the cylindrical surface **40** of the post **18.** The other surface *52b* is in metallic contact with the smooth inner cylindrical surface of the inertial member **70.** The two cylindrical surfaces *52a* and *52b* are concentric with the acceleration axis A—A of the accelerometer and the Z axis of the crystal. The upper and lower surfaces of the crystal are clear, that is free of conductive material.

The piezoelectric element **50** is annular, being in the form of a cylindrical ring having a central bore extending therethrough. The top and bottom walls of the element **50** are free of metallic material so that the two electrodes *54a* and *54b* are insulated from each other, thereby forming a capacitance in which the two plates provided by the electrodes are spaced apart by the dielectric material constituting the piezoelectric element **50.** The inner and outer faces of the crystal are cut and polished to an optical finish and the chromium and gold coatings are thin and of uniform thickness. Furthermore, the gold is sufficiently soft and malleable to assure complete even contact of those faces of the crystals with the post **18** and the inertial member **70.**

Small platinum wires (not shown) are bonded to the electrodes *54a* and *54b* by an electrically conductive adhesive, such as platinum-gold paste. In the best embodiment of the invention, after the crystal **50** is secured to post **18** and the mass **70** is secured to crystal **50,** the wire bonded to the electrode *54a* has its other end bonded with platinum-gold paste to the post **18,** and the wire bonded to electrode *54b* has its other end bonded to mass **70.** These wires provide electrical communication between the crystal **50** and post **18** and between the crystal **50** and mass **70.** The crystal **50** is bonded to the post **18** and the inertial mass **70** is bonded to the crystal **50** by a temperature-resistive, electrically insulating adhesive, such as porcelain cement or the like. Alternatively, the mechanical and electrical connections between the post **18** and the crystal **50** and between the crystal **50** and the mass **70** may be produced by brazing or the like.

The post **18** and the base **10** of the accelerometer **8** are formed of a metal, such as Waspaloy, which expands with temperature slightly faster than the expansion of the crystal **50.** The inertial mass **70** is formed of a metal, such as Inconel, which expands less rapidly than the expansion of the crystal **50.** The accelerometer **8** is constructed so that the crystal **50** is held firmly between the post **18** and the mass **70** at the lowest temperature range of the accelerometer. This construction maintains the crystal **50** in a constant state of compression throughout the entire range of operation of the accelerometer in order to insure that the crystal will remain in place on the post and that the inertial mass will remain in place on the crystal at all times.

In the embodiment of the invention illustrated in FIG. **1,** the acceleration sensing unit **16** is arranged concentrically on the post **18.** The inner face *52a* of the crystal **50** is electrically connected to the outer conductor **64** of the coaxial connector **60.** The outer face *52b* of the piezoelectric element **50** is electrically connected with the insulated hollow central inner conductor **62** of the cable connector **60.** The outer conductor **64** of the connector **60** is in the form of a threaded fitting mounting the conductor **60** on the base **10.** More particularly, the inner face *52a* is in electrical communication with the outer conductor **64** through the coating *54a* which is in conductive contact with the metallic post **18.** The connection of the outer face *52b* with conductor **62** is effected by electrical communication of the electrode *54b* with the metallic inertial member **70** which in turn is electrically connected to the central conductor **62** of the connector **60** by means of a lightweight flexible electrical connector **80.**

In the best embodiment of this invention known, the piezoelectric element **50** is in the form of a single lithium niobate crystal cut with its top and bottom parallel faces parallel to a Z plane that is perpendicular to the Z axis of the crystal. (FIG. **2**).

In this embodiment of the invention, the crystal is oriented in the accelerometer with the positive Z axis towards the base **10,** as shown in FIG. **2.** The positive portion of the other axes of this right-hand coordinate system are shown in FIGS. **2** and **3.**

It has been determined, experimentally, that the accelerometer of this invention employing a crystal of the 3m type, generates an output signal which is proportional to the component of acceleration parallel to the Z axis and is insensitive to components of acceleration in directions perpendicular to the Z axis. The accelerometer is also free of pryroelectric effects. These phenomena may be explained as follows.

Lithium niobate crystals are of the crystal class that have symmetry properties belonging to the 3m group. As illustrated in FIG. **2,** such a crystal has three mirror planes M that extend in directions parallel to the Z, or optical, axis. These planes intersect in pairs parallel to the optical or Z axis and they are separated by dihedral angles of 120°. The mirror planes are shown as if they originate in a common axis Z—Z. In fact, of course, the planes extend indefinitely so that each plane intersects the angle between each of the other two planes, thus accounting for the 120° separation between the planes. Because of the 3-fold symmetry, each mirror plane M may be considered to include a corresponding Y axis, which is perpendicular to the Z axis. Furthermore, the X axis with respect to each plane of symmetry lies in a direction perpendicular to both the Y axis and the Z axis. Stated differently, an X axis is perpendicular to each corresponding mirror plane M.

A 3m crystal is characterized by eight piezoelectric coefficients of which four are mutually independent, as illustrated in the following matrix:

TABLE I

	STRESS MODE					
	1	2	3	4	5	6
Output Mode	Compression Axis			Shear Axis		
	X	Y	Z	X	Y	Z
1. "X"	0	0	0	0	d_{15}	$d_{16}=-2d_{22}$

TABLE I—Continued

Output Mode	STRESS MODE 1	2	3	4	5	6
	Compression Axis			Shear Axis		
	X	Y	Z	X	Y	Z
2. "Y"	$d_{21}=-d_{22}$	d_{22}	0	$d_{24}=d_{15}$	0	0
3. "Z"	d_{31}	$d_{32}=d_{31}$	d_{33}	0	0	0

where the various piezoelectric coefficients d_{ij} have the values given in Table II.

TABLE II

	$LiNbO_3$	$LiTaO_3$	Tourmaline
d_{15}	68.	26.	3.7
d_{22}	21.	8.	−0.3
d_{31}	−1.	−3.	0.3
d_{33}	6.	9.	1.9

In the foregoing table, the values of the piezoelectric coefficients are given in units of picocoulombs per Newton (pC/N) for lithium niobate, lithium tantalate, and tourmaline.

In these tables, the first subscript of the term d_{ij}, refers to an electrode face of the crystal, and the second subscript refers to the type and direction of stress. The numbers 1, 2, and 3 represent compressive stress in the X, Y, and Z directions respectively, and the numbers 4, 5, 6 represent shear moments about the X, Y, and Z axes respectively.

For purposes of explanation, the annular crystal can be thought of as divided in small segments as indicated in FIG. **3.** If these imaginary segments are small enough, the circular walls become almost straight and each segment approximates a series of small cubes. The piezoelectric coefficients discussed above apply to cubes and these coefficients can be employed to explain the annular crystal's response to forces due to acceleration.

In FIG. 3 the Y-axis of the crystal passes through the center of segments R and L.

When the accelerometer is accelerated upward parallel to the Z—Z axis, there is an upward force on the crystal's inside diameter and a downward force on the crystal's outside diameter. For the segment R, this produces a positive shear couple about the X-axis and for the segment L, this produces a negative shear couple about the X-axis.

d_{24} is the coefficient employed to determine the charge on the segments R and L. A positive charge is produced on the positive Y surface **52*b*** of segment R and a negative charge is produced on the negative Y surface **52*a*** of segment R. A negative charge is produced on the positive Y surface **52*a*** of segment L and a positive charge is produced on the negative Y surface **52*b*** of segment L.

The surfaces **52*a*** of segments R and L are in electrical communication through electrode **54*a*** so that their negative charges are added together. Similarly, the **52*b*** surfaces of the segments R and L are electrically connected by electrode **54*b*** so that their positive charges are added together.

Segments located at positions 90° from the R and L segments operate similarly except that the d_{25} coefficient is employed to determine the charge, instead of the d_{24} coefficient. The d_{24} and d_{25} coefficients are numerically equal.

Charges on segment pairs at other locations in the crystal are determined by employing components of both the d_{24} and d_{25} coefficients. All of the **52*a*** surfaces of the individual segments are electrically connected together and all of the **52*b*** segments of the individual segments are electrically connected together. Therefore, the transducer is sensitive to acceleration in a direction parallel to the Z—Z axis, with the sensitivity determined by the d_{24} and d_{25} coefficients.

Acceleration in the negative Y direction parallel to the Y axis causes tensile stresses, or tension, in the segment R. d_{22} is the coefficient employed to determine the charge on the R segment. A charge is produced on the surface **52*b*** and an opposite charge is produced on the surface **52*a*** of the R segment.

Because of the 3-fold rotation symmetry of the crystal, there are two axes Y1 and Y2, each with a segment similar to the R segment discussed above. These segments are labeled R1 and R2 in FIG. **3.** Because of the annular symmetry of design of the crystal, segments R1 and R2 will be subjected to compression forces due to the acceleration of the crystal in the negative Y direction parallel to the Y axis. But the magnitude of the forces along the respective Y1 and Y2 axes of segments R1 and R2 are each one-half the total force applied to the segment R. $-d_{22}$ is the coefficient employed to determine the charges on the segments R1 and R2 when they are subjected to compression.

Therefore, when the crystal is subjected to acceleration in a negative Y direction parallel to the Y-axis, charges produced on the **52*a*** and **52*b*** surfaces of R1 and R2 have the opposite sign of charges produced on the **52*a*** and **52*b*** surfaces respectively of the R segment and the charges produced on segments R1 and R2 combine to cancel the charges produced on the R segment. The net result is no sensitivity to acceleration in a direction parallel to the Y axis.

In a somewhat similar manner, it can also be shown that there is no sensitivity to acceleration in any other direction perpendicular to the Z axis.

The pyroelectric axis of lithium niobate is the Z axis. Temperature changes will produce charges due to primary and secondary pyroelectric effects on the Z faces of the crystal. But since, in this embodiment of the invention, there is no electric communication with the Z faces, the transducer is not sensitive to the primary pyroelectric effect. Also, there is no sensitivity to uniform thermal expansion of the annular parts of the accelerometer. This is because segment pairs, such as are illustrated in FIG. **3,** produce opposite charges when subjected to such stresses, and, since the segments are in electrical communication, these charges cancel.

When the accelerometer of FIG. **1** is accelerated in a direction parallel to the Z axis, a charge is generated between the electrodes **54***a* and **54***b* that is proportional to the acceleration, and when the accelerometer is accelerated in some other direction, a charge is generated proportional to the component of acceleration along the Z axis.

Special precautions are taken to provide for long life of these accelerometers employing lithium niobate when they are used at high temperatures and low pressures, or in the presence of slightly reducing atmospheres. Such precautions are important because, as is well known, lithium niobate tends to be reduced, that is, lose its oxygen, when exposed to an atmosphere in which the partial pressure of oxygen is low. The rate of reduction increases with the temperature. Such reduction results in removal of some of the oxygen from the crystal, thereby reducing the electrical resistivity of the crystal. Such reduction is retarded, if not entirely prevented, by providing a perforation **30** in the wall of the case **12** to provide a channel for ingress of oxygen from the outer atmosphere into the cavity within the case.

In Table III some additional important properties of the various members of the 3m class mentioned, namely, lithium niobate, lithium tantalate, and tourmaline, are set forth.

TABLE III

CRYSTAL	$LiNbO_3$	$LiTaO_3$	Natural Tourmaline
Dielectric Const.	84	51	6.3
Coefficient of Thermal Expansion			
Axial	2	5.7	9.3×10^{-6}/°C
Radial	16.7	21	7.7×10^{-6}/°C
Curie Temp.	1210°C	610°C	None
Shear Modulus (N/M^2)	6	9.6	$- \times 10^{10} N/M^2$
Resistivity (ohm - cm)	5×10^8 at 400°C	2×10^5 at 575°C	Variable
Specific Gravity	4.6	7.4	3.0
Soluble in H_2O	No	No	No
Sensitivity to Primary Pyroelectric Effects	None	None	None
Sensitivity to Transverse Forces	None	None	None
Electromechanical Coupling Coefficient (K_{15})	Highest (0.45)	Intermediate (0.31)	Lowest —

In this table, the dielectric constant is the value in the radial direction divided by the dielectric constant of free space and the shear modulus is the stress divided by the strain about the X axis.

Examination of Table III shows that lithium niobate preserves its piezoelectric properties to the highest temperatures and also the highest electromechanical coupling coefficient.

This invention has been described with reference to an annular accelerometer because of the particular usefulness of the invention in such accelerometers. However, this invention may also be employed in other types of force actuated transducers, such as pressure transducers.

It is thus seen that this invention provides an accelerometer which may be employed for a prolonged period at high temperatures; and when employing lithium niobate in the form shown, the invention provides an accelerometer which is capable of use at high temperatures for prolonged periods; and in particular provides such an accelerometer of high sensitivity. Though the accelerometer of this invention is particularly suitable for use at high temperatures, because of the fact that the crystal material possesses high electromechanical efficiency (ratio of electrical power generated to the mechanical power applied to the crystal), it is also advantageous to employ the accelerometers at low temperatures.

The invention claimed is:

1. In a transducer of the shear type in which an electrical signal is developed across two parallel cylindrical surfaces of an annular piezoelectric element mounted to move relatively to each other in a direction parallel to such surfaces in response to force applied to at least one of said surfaces in said direction and in which means are provided for conducting such electrical signal to a utilization device responsive thereto, the improvement wherein said annular piezoelectric element comprises a piezoelectric crystal of the 3m class having its Z axis parallel to said surfaces.

2. In a transducer of the shear type in which an electrical signal is developed across two parallel cylindrical surfaces of an annular piezoelectric element mounted to move relatively to each other in a direction parallel to such surfaces in response to force applied to at least one of said surfaces in said direction and in which means are provided for conducting such electrical signal to a utilization device responsive thereto, the improvement wherein said annular piezoelectric element comprises a lithium niobate crystal having its Z axis parallel to said surfaces,

and means providing communication between said crystal and an oxygen-containing atmosphere.

3. In a transducer of the shear type in which an electrical signal is developed across two parallel cylindrical surfaces of an annular piezoelectric element mounted between two members which are adapted to move relatively to each other in a direction parallel to such surfaces in response to said relative motion of said two members and in which means are provided for conducting such electrical signal to a utilization device responsive thereto, the improvement wherein said annular piezoelectric element comprises a piezoelectric crystal of the 3m class havings its Z axis parallel to said surfaces.

4. A transducer as defined in claim **3** comprising an accelerometer in which one of said two members constitutes an inertial member resiliently supported by said element from the other of said two members and wherein said electrical signal is developed in response to the acceleration of an object that is secured to said other of said two members.

5. An accelerometer as defined in claim **4** wherein one of said members has a base provided with a base surface attachable to the surface of said accelerating object, said base surface being normal to said Z-axis.

6. A transducer as defined in claim **3** in which said element has a central hole therein and one of said two members extends through said element, said two members being composed of metal.

7. A transducer as defined in claim **3** in which said element has a central hole therein, and one of said two members extends through said element, the other member being of annular configuration, and wherein said two members are composed of electrically conductive material, the parallel surfaces of said piezoelectric element being in electrically conductive relation with said respective members.

8. A crystal body as defined in claim **7** wherein each said coating comprises an inner layer of electrically conductive material and an outer layer of non-corrosive, malleable, electrically conductive material.

9. A crystal body as defined in claim **8** wherein said inner coating is bonded to and covers the inner parallel cylindrical surface of said crystal and is composed of a thin layer of chromium and said outer coating is secured to and covers the outer surface of said inner electrode, said outer electrode being composed of a thin layer of gold.

10. In a transducer of the shear type in which an electrical signal is developed across two parallel cylindrical surfaces of an annular piezoelectric element mounted between two members which are adapted to move relatively to each other in a direction parallel to such surfaces in response to said relative motion of said two members and in which means are provided for conducting such electrical signal to a utilization device responsive thereto, the improvement wherein said annular piezoelectric element comprises lithium niobate having its Z axis parallel to said surfaces.

11. A transducer as defined in claim **10** including means to apply a force to at least one of said surfaces in said direction of movement.

12. A single crystal body comprising an annular crystal of the 3m class having two parallel cylindrical surfaces parallel to the Z axis of said crystal.

13. A single crystal body as defined in claim **12** wherein said body is composed of lithium niobate.

14. An article of manufacture comprising a crystal body as defined in claim **12** wherein said cylindrical surfaces have coatings of electrically conductive material on them.

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