MULTI-MODE ACCELEROMETER

An accelerometer (10) having a piezoelectric transducer (22) which produces electrical signals in response to its deflection and comprises an elongated, continuous beam of generally flat configuration and narrow cross section to provide a bending axis which facilitates deflection of the free ends in response to shock in one or more of the linear and torsional modes. The beam is supported intermediate its ends by a mount (29), with the free ends of the beam preferably extending equidistantly in opposite directions from the mount. By laminating a single piece of piezoelectric material to a rigid substrate and forming cantilevers in each deflection direction, an accelerometer with six degrees of freedom may be formed. Also, a compressive type angular accelerometer (122) may be formed from two piezoelectric sensor elements incorporated onto a single piece of piezoelectric polymer (126).
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MULTI-MODE ACCELEROMETER

BACKGROUND OF THE INVENTION

Field of the Invention

The present invention relates to a miniature multi-mode accelerometer which responds to acceleration in several different transverse and angular directions. In particular, the present invention is directed to increasing the sensitivity, accuracy and compactness of such an accelerometer and is further directed to reducing the cost of its manufacture.

The multi-mode accelerometer described herein operates in one or more linear modes along X, Y and Z axes which are orthogonally disposed, i.e., in planes at right angles to one another, and also in angular or torsional modes about the X, Y and Z axes. The present accelerometer is operable in one or several of such modes and is especially useful on disk drives of notebook-size computers and on other shock-sensitive portable or hand-held equipment.

Notebook-size computers employ small-diameter hard disk drives for data storage, that is, the information is magnetically stored on closely spaced tracks of rotatable discs. In the event that the disk drive experiences shock during the read/write operation, an improper read or write to the disk may take place. Accelerometers are employed in accordance with the invention to detect the shock and initiate a response. A multi-mode accelerometer constructed according to the present invention initiates an interruption of the
read/write operation in response to shock above a predetermined level in one or more of the modes previously described. In addition, the accelerometer signal may be used in a feedback loop to control the position of the read/write arm, such as to reverse or otherwise reposition the arm in the event of shock. Furthermore, the accuracy, dependability, low cost, and thumbnail size of the accelerometer herein described is well suited for advanced hard drive and notebook-size computer apparatus.

Although a multi-mode accelerometer is disclosed herein, it may be configured advantageously to respond solely to torsional mode acceleration. Such a single mode accelerometer will be less expensive to manufacture, and the complexity and cost of electrical interfacing will also be reduced.

The construction of the disc drive shown and described in U.S. Patent No. 4,831,476, issued May 16, 1989 to P. J. Pisczak, is incorporated herein by reference for the sake of brevity in disclosing apparatus of the type with which the present invention is operatively associated and has its principal utility in a preferred embodiment.

Description of the Prior Art

The present invention is an improvement upon the accelerometers and transducers of the type disclosed by way of example in U.S. Patent No. 4,996,878 of John Kubler which issued on March 5, 1991 and in U.S. Patent No. 4,431,935 of B.F. Rider which issued on February 14, 1984.

The Kubler transducer employs two identical oscillating beams of piezoelectric material, separated electrically, and fixed by their respective mountings to a base for measuring linear and angular acceleration. Electrical contacts are attached to the upper and lower side of each beam, and lines are attached to the contacts for interconnecting the piezoelectrical elements and for taking off the signals generated. Unfortunately, the transducer of Kubler uses two beams which have unmatched electrical characteristics which, in
actual practice, require compensating circuitry and adjustment. Such compensating circuitry is undesirable since it increases the cost and complexity of the accelerometer.

The Rider sensor structure is mounted on the object being monitored for rotation therewith, and it comprises a plurality of piezoelectric plates preferably arranged in a laminated structure. However, the Rider sensor structure is quite complicated, has unpredictable electrical characteristics, and is difficult to mount on an object for rotation therewith. A simplified and inexpensive accelerometer is thus desired.

SUMMARY OF THE INVENTION

The present invention seeks to avoid the deficiencies of Kubler's two oscillating beams that are electrically unmatched. It also seeks to avoid the deficiencies of Rider's multiple transducers laminated together in view of their unpredictable electrical characteristic and mounting difficulties on an object for rotation therewith. For these purposes, a first embodiment of the present invention employs one, centrally mounted piezoelectric member with a unitary, full length, common conductor on one surface of the piezoelectric member and separate electrodes on the other surface thereof to provide a multi-mode accelerometer which is capable of performing electrical differencing by itself and which may serve as both a linear and an angular accelerometer.

In a second embodiment of the invention, two or more of such piezoelectric members are formed from a single piece of piezoelectric material for sensing acceleration in different angular directions, while in a third embodiment, a mass is placed on the conductor(s) on one side of a piezoelectric film to apply a compressive rather than a bending force for providing a multi-mode accelerometer which may also serve as a linear and an angular accelerometer.

The present invention thus relates to a multi-mode accelerometer for sensing the acceleration in at least one angular direction of movement of an object. Such an
accelerometer in accordance with the first embodiment of the invention preferably comprises a substantially flat, elongated beam structure comprising a piezoelectric film transducer which produces electrical signals proportional to its deflection, a common electrode on a first side of the piezoelectric film transducer, and first and second electrodes on a second side of the piezoelectric film transducer which is opposite the first side. In accordance with the invention, the first and second electrodes are electrically isolated from each other and thus together with the common electrode form two piezoelectric sensing elements from a single piezoelectric film. A support structure is also provided for supporting the elongated beam structure at a mid-section thereof so that end portions of the elongated beam structure on either side of the mid-section may deflect in opposite directions in response to angular movement of the elongated beam structure in the sensed angular direction.

In preferred configurations of the first embodiment of the invention, the common electrode comprises a rigid conductive beam. The support structure may also comprise three conductive elements which respectively contact the common electrode and the first and second electrodes so as to form electrical contact therewith and to support the beam structure with respect to the object.

Alternatively, the beam structure may comprise a nonconductive beam for supporting the piezoelectric film transducer and the common, first and second electrodes. In this configuration, the nonconductive beam may comprise a central notch through which the piezoelectric film transducer passes such that one end of the piezoelectric film transducer is on one side of the nonconductive beam and another end of the piezoelectric film transducer is on the other side of the nonconductive beam. To facilitate electrical connections, such an embodiment may further comprise tab portions on the first and second electrodes for insertion into a printed circuit board having slots for accepting the tabs.
Preferably, three of such accelerometers are provided along the X, Y and Z axes for sensing the angular acceleration of an object about the X, Y and Z axes.

In a second embodiment of the multi-mode accelerometer of the invention, the accelerometer senses the acceleration in at least first and second angular directions of movement of the object. Such an accelerometer in accordance with the invention preferably comprises a piezoelectric sensor comprising a thin conductive sheet laminated on one side thereof to a piezoelectric film transducer which produces electrical signals proportional to its deflection. The conductive sheet functions as a common electrode and as a structural support on a first side of the piezoelectric film transducer. First and second electrodes are also disposed on a second side of the piezoelectric film transducer which is opposite the first side, and the first and second electrodes are electrically isolated from each other so as to form with the common electrode two separate piezoelectric sensors using a single piezoelectric film.

Preferably, the piezoelectric transducer of the second embodiment has a first portion thereof which includes a first substantially flat, elongated beam structure which is supported at a mid-section thereof so as to deflect in opposite directions at end portions thereof on either side of the mid-section in response to angular movement of the first elongated beam structure in the first angular direction. In order to sense acceleration in a second angular direction, the piezoelectric transducer of the second embodiment further comprises a second portion thereof which includes a second substantially flat, elongated beam structure which is connected at a mid-section thereof to the object and has free ends on either side of the mid-section which are at respective angles to the object so as to deflect in opposite directions in response to angular movement of the second elongated beam structure in the second angular direction. A support structure is also provided for connecting the second elongated beam structure at the mid-section thereof to the object so as to
allow deflection is the first and second angular directions in response to movement of the object.

In addition, the piezoelectric transducer of the second embodiment may have a third portion thereof which includes a third substantially flat, elongated beam structure which is supported at a mid-section thereof so as to deflect in opposite directions at end portions thereof on either side of the mid-section in response to angular movement of the third elongated beam structure in a third angular direction, thereby allowing measurement of angular acceleration about all of the coordinate axes.

In a third embodiment of the multi-mode accelerometer of the invention, the accelerometer comprises a substrate, a piezoelectric film transducer disposed on a surface of the substrate, the piezoelectric film transducer comprising a piezoelectric film for producing electrical signals proportional to its deflection, a common electrode on a first side of the piezoelectric film, and first and second electrodes on a second side of the piezoelectric film which is opposite the first side. Preferably, the first and second electrodes are electrically isolated from each other so as to form two piezoelectric sensors from a single piezoelectric film.

However, unlike the first and second embodiments, the third embodiment further comprises a mass attached to a side of the piezoelectric film transducer opposite the substrate for imparting stress to the piezoelectric film during acceleration in at least one angular direction. In this embodiment, acceleration in the sensed angular direction is proportional to the stress applied to the piezoelectric film by the mass.

In a first configuration of the third embodiment, the mass comprises a first portion substantially centered over the first electrode and a second portion substantially centered over the second electrode so that it stress the piezoelectric film in response to angular acceleration in the sensed angular direction at a sensitivity functionally related to a distance between the first and second portions of the mass. Alternatively, the mass may be substantially centered over the
first electrode so that it stresses the piezoelectric film in response only to linear acceleration of the mass.

The piezoelectric film transducer of the third embodiment may further comprise an insulator between the first and second electrodes and the mass, whereby the first side of the piezoelectric film and the common electrode are disposed adjacent the substrate. The output of the transducer is then obtained via an amplifier. In a first configuration, the first electrode is grounded and the electrical signals are applied to the amplifier via the second electrode. Alternatively, a differential amplifier may be connected at respective inputs thereof to the first and second electrodes.

As will be appreciated by those skilled in the art, since the accelerometer of the respective embodiments of the present invention utilizes a simple, continuous, piezoelectric film as the active element of the sensor, the deflecting portions are well matched, surely better matched than two separate piezoelectric films. Therefore, the present accelerometer does not require the matching or compensating circuitry of prior art accelerometers.

The sensor of the present invention preferably includes a housing for the sensor, with its mount secured in a stationary position on that housing. Unlike the Rider construction, the present housing is mounted, not for rotation with a rotating object, but it is fixedly mounted on a non-rotating object for monitoring the acceleration of that object in both linear and torsional modes. For example, the accelerometer of the invention is preferably mounted on a casing of a hard disk drive or other non-rotatable surface of a portable computer. Preferably, the sensor circuitry further includes a read/write interrupt device operatively associated with a data buss and a read/write disk, whereby upon receipt of signals at a predetermined level from the sensor, the interrupt device interrupts the transfer of data between the data buss and the read/write disk, with the result that read/write errors caused by shock to the computer are prevented. Alternatively,
the signal may be employed to reverse or otherwise reposition
the arm in the event of shock.

BRIEF DESCRIPTION OF THE DRAWINGS

The objects and advantages of the invention will
become more apparent and more readily appreciated to one of
ordinary skill in the art from the following detailed
description of the presently preferred exemplary embodiments of
the invention taken in conjunction with the accompanying
drawings, of which:

Figure 1 is a perspective view of a disk drive unit
having the accelerometer of the present invention mounted on a
read/write head, shown with its cover removed and with a
portion of the housing broken away.

Figure 2 is a perspective view of an accelerometer
showing the X, Y and Z axes in broken lines, and with arrows
indicating the torsional mode.

Figure 3 is a block diagram showing the functional
relationship of the accelerometer to the computer data buss,
the magnetic storage media, and the read/write interrupt
device.

Figure 4 is a perspective view of a notebook size
portable computer employing the invention, with a portion of
the computer casing broken away to show an internally
positioned hard disk drive unit embodying the invention.

Figure 5 is an enlarged perspective view of a first
embodiment of an accelerometer embodying the invention, its
casing mounted on the surface of an object being monitored, and
the cover of its casing removed to provide a view of the
interior.

Figure 6 is an enlarged perspective view of a
transducer element employed in the accelerometer of Figure 5.

Figures 7(a) and 7(b) illustrate the principle
concepts embodied in a beam type piezoelectric rotational
accelerometer mounted on an insulative beam (Figure 7(a)) or a
conductive beam (Figure 7(b)) for use in the configuration
illustrated in Figure 5.
Figure 8 is a schematic view of the transducer and its electrical circuitry, showing deflection and polarity of the transducer in the torsional mode.

Figure 9 is a schematic view of the transducer and its electrical circuitry, showing deflection and polarity of the transducer in the linear mode.

Figure 10 is an equivalent electrical circuit of the transducer element of Figure 6 when installed as in Figure 5; Figure 11 is a view, partly perspective to show a three-axis mount for a multi-mode accelerometer and partly schematic to show associated electronic circuitry for an accelerometer for sensing angular acceleration about the X, Y and Z axes;

Figure 12 is a longitudinal cross-sectional view of a modified transducer of the type illustrated in Figure 5; and Figure 13 is a longitudinal cross-sectional view of another modified transducer of the type illustrated in Figure 5.

Figures 14(a) - 14(c) illustrate a double cantilever beam formed from a single piece of piezoelectric material which is mounted at its center to a circuit board.

Figure 15 is a perspective view of a second embodiment of a piezoelectric sensor including a "winged" section responsive to shock in the X - Y and Y - Z planes.

Figures 16(a) - 16(c) respectively illustrate front, left-side and unfolded views of an embodiment of a piezoelectric sensor which is responsive to shock in any dimension.

Figures 17(a) and 17(b) respectively illustrate front and left-side views of another embodiment of a piezoelectric sensor which is responsive to shock in any dimension.

Figures 18(a) and 18(b) respectively illustrate front and top views of still another embodiment of a piezoelectric sensor which is responsive to shock in any dimension.

Figures 19(a) and 19(b) respectively illustrate a compressive-type rotational accelerometer in accordance with a third embodiment and its equivalent circuit.
Figure 20 illustrates a compressive-type linear accelerometer in accordance with the third embodiment of the invention.

Figure 21 illustrates an equivalent circuit for a rotational and linear accelerometer designed in accordance with the third embodiment of the invention.

Figures 22(a) - 22(c) respectively illustrate alternative configurations for an angular accelerometer and their equivalent circuit in accordance with the third embodiment of the invention.

Figures 23(a) - 23(c) respectively illustrate additional alternative configurations for an angular accelerometer and their equivalent circuit in accordance with the third embodiment of the invention.

**DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT**

A multi-mode accelerometer in accordance with the presently preferred exemplary embodiments of the invention will be described below with reference to Figures 1-23. It will be appreciated by those of ordinary skill in the art that the description given herein with respect to those figures is for exemplary purposes only and is not intended in any way to limit the scope of the invention. For example, a preferred embodiment of the invention is described for use as a shock sensor in a notebook-size computer. Of course, the accelerometer of the invention may be used in many different products such as automobiles, seismic detectors and other rotating machinery for modal analysis and active vibration damping in many different configurations. Accordingly, all questions regarding the scope of the invention should be resolved by referring to the appended claims.

Figure 1 illustrates a hard disc drive 30 having an accelerometer 10 affixed to a read/write head 32. Alternatively, the accelerometer designated 10' may be rigidly mounted on the housing 31 of the drive 30 as shown or the accelerometer designated 10'' may be affixed to the circuit board 33 within housing 31.
The read/write head 32 is installed at the free end of a read/write arm 34, movable in a limited arcuate range about an upright arm-positioning shaft 36. Also attached to the same shaft 36 is a locating arm 38 on the end of which is a position detector 40. Detector 40 cooperates with locating disk 42 at its locating surface 43 to signal the track and sector position of the read/write head 32 relative to the read/write discs 44. The accelerometer 10 is installed on head 32 for maximum responsiveness to head movement in the hard disk drive.

It is the function of the accelerometer 10 to respond to shock, such as to detect or measure the acceleration of the object on which it is mounted. The accelerometer 10 responds in one or more linear modes along orthogonal X, Y and Z axes shown in Figure 2, and torsionally about one or more of the axes as indicated by the arrows in Figure 2. The accelerometer 10 includes electronic circuitry which is described below.

The risk of read/write error due to shock increases with the downsizing of hard disk drives to fit into notebook-size computers. Mild shocks which previously could be tolerated now produce movement of the read/write head off the proper track to and beyond the adjacent track. This is because downsizing has reduced the distance between adjacent tracks of the disk, i.e., the magnetic storage media. It follows that the risk of read/write error due to shock in portable computers is exacerbated by downsizing of the disk, and the present invention addresses that concern.

The hard disk drive 30 with an accelerometer 10 in accordance with the invention may be installed in a notebook-size portable computer 45 as shown in Figure 4. The accelerometer 10 is there operatively associated with the hard disk drive 30. As shown in Figure 3, data flows from computer buss 46 to magnetic storage media provided by read/write discs 44 under control of an electronic read/write interrupt device 48. In response to a signal from the accelerometer 10, the interrupt device 48 either allows or interrupts the flow of data between the buss 46 and the disc storage media 44, in
either direction, or the signal may be used in a feedback loop to control repositioning of the head 32.

This mounting location is most sensitive in computer 45 for interruption of the read/write operation during shock to prevent read/write error. As shown in Figure 4, the computer 45 includes a case 49 with keyboard 50, video monitor 52 with screen 54, and hinge structure 55. A hard disk drive 30 having an accelerometer 10 is mounted in the case 49.

Beam-type Piezoelectric Sensor Embodiments

Figure 5 illustrates a miniature, multi-mode accelerometer 10 embodying the invention. The accelerometer 10 is housed by a case 12 having a base 14 rigidly secured to the surface 16 of an object 18. A cover for the case 12 is removed and not shown in Figure 5, but it is in place in Figure 2. The case 12 further includes upright wall structure 20 surrounding an elongated transducer element 22. The element 22 is securely gripped and supported above the base 14 between a pair of fingers serving as conductive elements 24, 26 on one side of the element and another finger 28 serving as third conductive element on the other side thereof. The fingers 24, 26, 28 comprise a mount 29. An effective electrical connection is also made by the force of engagement between the mutually facing contact surfaces as a result of wedging the element 22 between the finger 28 and the pair of fingers 24, 26.

As shown in Figure 6, the beam-type accelerometer 10 is provided with a single piezoelectric transducer element 22. This element 22 preferably comprises a thin, elongated strip of beryllium copper providing the common conductor 56 laminated with adhesive to a single, similarly shaped sheet 59 of polarized polymeric piezoelectric material, preferably polyvinylidene fluoride (PVDF). As an alternative to sheet 59, a layer of polarized piezoelectric material such as VF₂VF₃ may be cast against the common conductor 56. The PVDF sheet 59 is procured with piezoelectric properties because in its manufacture it was stretched and subjected at elevated
temperature to a large electric field to induce permanent piezoelectric activity.

As an alternative to a laminate of the PVDF sheet 59 and beryllium copper common conductor 56 as shown in Figure 6, a metallic deposit of conductive material on a thicker and therefore stiffer sheet 59 of PVDF material may be substituted. Preferably the deposited material forming conductor 56 is nickel, although silver, aluminum, gold and carbon are among other suitable materials.

Midway between the ends of the PVDF sheet 59, on the side opposite the common conductor 56, as shown in Figure 6, is an uncoated area 60 of sheet 59 which extends across the entire width of the element 22. On the same side as the uncoated area 60, and covering the remainder of this surface are metallic deposits serving as the output electrodes 57, 58. Each electrode 57, 58 extends from the uncoated area 60 to the associated free end of the transducer element 22.

Fixedly supporting the transducer element 22 at a point intermediate its ends is the mount 29 whose conductive elements or fingers 24, 26 respectively contact the output electrodes 57, 58, and whose conductive element or finger 28 contacts the common conductor 56, as shown in Figure 5. Thus supported by mount 29, the free ends of the beam defined by transducer element 22 extend equidistantly in opposite directions from the mount 29. The free ends of the beam deflect in the same direction, as shown in Figure 9, in response to shock in the linear mode along the X or Z axis; and they deflect in opposite directions, as shown in Figure 8, in response to shock in the torsional mode about the Z axis.

The mount 29 employs the conductive elements or fingers 24, 26 and conductor 28 not only for making electrical contact or engagement with opposite sides of the transducer element 22, but also to clasp the transducer element 22 when engaging it on opposite sides thereof. Thus, two of the conductive elements of the mount 29, i.e., the fingers 24, 26, engage and provide leads to the output electrodes 57, 58, and
the third of the conductive elements or fingers 28 engages and provides a lead to the common conductor 56.

With the transducer element 22 inclined at an angle of 45 degrees to the base 14 of the casing 12 and the underlying surface 18 of the object 10 on which it is mounted, the accelerometer 10 responds to linear shock in a plane containing the X axis, which plane is parallel to the surface of the base 14 of casing 12, and to the surface 18 of the object 16 being monitored. The accelerometer also responds to linear shock in the direction of the Z axis which is perpendicular to the X axis and preferably normal to the surface 18 and the base 14. An accelerometer of this construction is virtually insensitive to linear shock along the longitudinal axis of the transducer element 22 and sensitive to shock transverse to the longitudinal extent of the transducer element 22. It is also most sensitive in the torsional mode where the cross section of the element 22 offers the least resistance to bending. Although the Z axis is shown normal to the surface 18 in Figure 2, it will be most sensitive at the angle of inclination of the element 22.

The construction and arrangement is such that in response to linear acceleration there is common mode rejection because the two ends of the element 22 vibrate in unison, that is, both ends deflect in the same direction and produce the same voltage of the same polarity to the output electrodes 57, 58. On the other hand, in torsional mode the ends of the transducer element 22 move in opposite directions, out of phase, producing the same voltage of opposite polarity to the output electrodes 57, 58.

The principle concepts embodied in such a beam type, piezoelectric rotational accelerometer will be apparent to one skilled in the art upon reference to Figures 7(a) and 7(b). As known to those skilled in the art, a rotational accelerometer can be made by subtracting the signals from two perfectly matched linear accelerometers that are rotating about a common point. In the accelerometer in the embodiment of Figure 5, two linear accelerometers are actually designed using a single
piece of piezoelectric polymer laminated to a rigid substrate (conductor) to form a cantilever beam structure, with the differencing actually done by the film electrode pattern itself. Then, when the beam structure is bent, in-plane stresses are applied to the piezoelectric film element causing a charge to be generated that is proportional to the amount of induced bend. Thus, when the beam structure is accelerated in a direction perpendicular to the plane of the beam, the beam will bend and produce a signal that is generally proportional to and of the proper sign for the direction of acceleration. The resulting structure also has very low sensitivity to transverse acceleration.

For example, as illustrated in Figure 7(a), the center support post or mount 62 of the piezoelectric sensor 61 is assumed to be mechanically coupled to the vibrating surface of interest, such as read/write head 32. If a purely linear acceleration is applied to the read/write head 32, (acceleration "a" in Figure 7), the resulting voltage between electrodes 57 and 58 is approximately zero. This is because both sides of the insulative beam 63 vibrate in unison about center support post 62 causing the piezoelectric film 59 to produce no net output due to a difference in film polarity. The common mode rejection ratio (CMRR), i.e., how close the output is to zero, is controlled by how closely matched the insulative beam 63 is on either side of the center post 62. On the other hand, if rotational acceleration is applied to the piezoelectric sensor 61, each end of insulative beam 63 vibrates of phase causing a net output which is proportional to the angular acceleration level. As will be appreciated by one skilled in the art, a good CMRR is thus obtainable using the device of Figure 5 since differencing is done with one piece of piezoelectric film which need not be matched.

Alternatively, as illustrated in Figure 7(b), the insulative beam 63 of sensor 61 can be replaced by conductive beam 63' of sensor 61' which provides the common electrode to further simplify construction and signal output connections.
If output voltages are measured for the deflection conditions shown in Figure 8, it can be seen that a net potential difference in voltage $V_{24}-V_{26}$ is obtained in the torsional mode of the piezoelectric sensor of the invention. However, under the conditions of Figure 9, in the linear deflection mode, a potential in voltage $V_{24}-V_{26}$ does not exist because the terminals are at the same potential. Thus, a voltage $V_{24}-V_{26}$ is obtained only when torsional deflection occurs as shown in Figure 8. In the case of either linear or torsional deflection, voltage potentials exist at $V_{26}, V_{24}-V_{26}$, and $V_{24}-V_{26}$ in proportion to deflection, and these values are useful for determining displacement, velocity and acceleration.

The equivalent circuit of Figure 10 shows the now well known parts of Figures 8 and 9, except that the transducer element 22 is designated $22_a$ and $22_b$ for the parts thereof at the two free ends, with their polarities as indicated.

**Alternative beam-type piezoelectric sensor embodiments**

Although a polymeric material is preferred for the element 22, a ceramic piezoelectric material may be employed for specific embodiments of the invention.

As another possible variation of the first embodiment of the invention, although casting of the piezoelectric layer onto conductor 56 is desired, this may be accomplished by laminating the layer onto the conductor 56.

The elongated transducer element 22 is desirably constructed with all non-conductive materials on its exposed surfaces, thus providing a beam movable in the bending mode having an exterior which is non-conductive.

The embodiment of Figure 5 has been shown with the element 22 mounted at a 45 degree angle to the base 14 of the casing 12, and at 45 degrees to the surface 18 of the object whose acceleration is being measured. In this context, it is the width or transverse extent of the long, flat element 22 that is so mounted. It is to be understood, however, that the element 22 may be mounted parallel to the base 14 and surface
18, or optionally at a right angle to the base 14 and surface 18. In these alternative mounted positions, the element 22 is most sensitive when bending about its narrowest cross section; therefore, the accelerometer of the present invention is well suited for use as a single mode, e.g., torsional mode, accelerometer when alternatively mounted as described.

A configuration of the present invention for multi-mode shock sensing utilizes three single-mode accelerometers 10 respectively mounted on object surface 16, as shown in Figure 11, by means of mount 64. Mount 64 has three surfaces 65, 66, 67 which are respectively oriented orthogonally relative to the X, Y and Z axes. The three accelerometers 10 are independently mounted on the respective surfaces 65, 66, 67 for measuring acceleration. Each is equipped to measure acceleration in a selected mode and is operatively associated with an amplifier 68 and an amplifying circuit for the signal generated. The mode selected for measurement is likely to be torsional but it may measure in linear mode as well or instead. Whether used to measure one or more modes of acceleration on each of the three surfaces of mount 64, the three accelerometers 10, used in combination, comprise a multi-mode accelerometer in accordance with an alternative configuration of the invention.

Figure 12 illustrates a variation 22' of the element 22 shown in Figure 6. The element 22' of Figure 12 includes a strip 59 of metallized, piezoelectric polymer material, carried by a non-conductive beam 70. The beam 70 has a central notch 72 whereby one end of the strip 59 is on one end at one side of the beam 70, and extends through the notch 72 to extend to the other end at the other side of the beam 70. Adhesive or laminating processes may be employed to secure together broad surfaces of the strip 59 and beam 70. The beam 70 may be non-conductive throughout or of conductive material with a non-conductive coating.

Figure 13 illustrates another variation 22" of the element 22 shown in Figure 6. In Figure 6, element 22" comprises a beam 70 which is adhesively secured or laminated to one side of the metallized, piezoelectric polymer strip 59.
Here, however, the opposite end portions of the strip 59 are oppositely spot- poled. More particularly, the element 22" of the beam structure includes a transducer strip 59 of continuous piezoelectric material poled at one end thereof with positive polarity along one side thereof and negative polarity on the opposite side thereof, and poled at the other end thereof with negative polarity along one side thereof and positive polarity on the opposite side thereof.

As known to those skilled in the art, an angular or rotary accelerometer may be formed from two linear accelerometers mounted on a common plane and spaced a distance apart. As noted above, by subtracting the signals from the two accelerometers, the amplitude of angular acceleration can be determined independent of any transverse or linear acceleration in any plane. Figures 14(a) - 14(c) illustrate an angular accelerometer formed from two cantilever beam acceleration sensors that are located and configured to detect any angular acceleration about the same axis on which the actuator arm rotates. In particular, as illustrated in Figure 14(a), the double cantilever beam can be formed from a single piece of beam 74 which is formed from a material such as standard PC board material. The beam is preferably supported in the center via, for example, pads 76 which connect the sensor to circuit traces on a circuit board 82 (Figure 14(c)). The resulting structure has a left beam and a right beam including metal electrodes 78 on its surface and a single piece of piezoelectric film 80 which is cut and mounted in such a way that it is laminated to the front side of the left beam and the back side of the right beam (Figure 14(b)) in the manner described above with respect to Figure 12.

The structure of Figures 14(a) - 14(c) senses angular acceleration about an axis in the plane of the beams 74 and perpendicular to the length of the beams 74. When accelerated clockwise about this axis, the left beam and the right beam both bend counter-clockwise. This causes the piezoelectric film on each beam to produce signals of the same polarity, which add to produce an output signal. On the other hand, when
the acceleration is counter-clockwise, the same thing happens except that the polarity of the signals is reversed. In addition, when the sensor of Figures 14(a) - (c) is subjected to linear acceleration that is in the plane of the beams, there is no beam bending and no electrical output signal. Finally, when the sensor is subjected to linear acceleration that is perpendicular to the beams, the left beam bends counter-clockwise and the right beam bends clockwise. The piezoelectric film 80 in each beam thus produces equal electrical signals but of opposite polarity, with a resultant output signal of zero.

Figure 15 is a perspective view of a second presently preferred embodiment of the invention whereby the cantilever beam sensor of Figures 14(a) - 14(c) further includes a "winged" portion for sensing acceleration in the X-Y and Y-Z planes as well as the X-Z plane. As illustrated, the sensor of Figure 15 includes the cantilever beam portion 84 with electrodes 86 which connect to circuit traces on circuit board 82. Circuit board 82 may then, in turn, be mounted on a read/write head 32 and the like for measuring mechanical shock sensations. As shown, the "winged" portion of the sensor includes a base which is substantially perpendicular to the cantilever beam 84 and mounted at 94 to the circuit board 82. "Winged" portions 88 are inclined at respective angles \( \theta \) and \( \phi \) (preferably \( \theta = \phi = 45^\circ \)) to the circuit board 82 and include electrodes 90 and 92 which are preferably connected to the circuit traces at 94. In order to operate, the cantilever beam 84 and "winged" portions 88 are laminated with a unitary piezoelectric material which outputs electrical signals in response to acceleration in at least 4 of the 6 possible degrees of freedom.

Figures 16(a) - 16(c) respectively illustrate front, left-side and unfolded views of an embodiment of a piezoelectric sensor which is responsive to shock for all 6 degrees of freedom. In particular, the sensor of Figure 16 is formed by bending a laminate of a piezoelectric material and a conductive electrode as shown in Figure 16(c) along the dotted fold lines
to form the sensor shape illustrated in Figures 16(a) and 16(b). As shown in Figures 16(a) and 16(b), the cantilever beam 96 is folded substantially perpendicularly to another cantilever beam 98 having left beam 99 and right beam 100, which is, in turn, folded substantially perpendicularly to cantilever beam 102 having "winged" portions 104 and 106 which are substantially perpendicular to all of the cantilever beams. The resulting sensor is then mounted to a circuit board at the center of cantilever beam 102 so that acceleration in the 3 rotational and translational directions may be sensed.

Figures 17(a) and 17(b) respectively illustrate front and left-side views of another embodiment of a piezoelectric sensor which is responsive to shock for all 6 degrees of freedom. As in the embodiment of Figure 16, a piezoelectric material is laminated to a conductive material in the desired shape, and the resulting material is folded to form cantilever beams 108, 109 and 110 with "winged" sections 112 and 114. The resulting structure is then connected at 115 to circuit traces as indicated in Figure 17(b).

Figures 18(a) and 18(b) respectively illustrate front and top views of still another embodiment of a piezoelectric sensor which is responsive to shock for all 6 degrees of freedom. This embodiment includes cantilever beams 116 and 120 with modified "winged" portions 117 and 118 for sensing angular acceleration in the X-Y and Y-Z planes. As in the above embodiments, the piezoelectric material may be laminated or coated on either side of a conductive metal beam which is bent as indicated. Of course, many other similar configurations within the teachings of the invention will become apparent to those skilled in the art.

Compressive-type Piezoelectric Sensor Embodiments

The following third embodiment of the invention differs from the variations of the first and second embodiments described above in that the piezoelectric elements are squeezed or compressed rather than bent to get an output electrical signal. As in the first and second embodiments, the second
embodiment has a continuous piezoelectric element with segmented electrodes for use as a rotational and translational accelerometer for measuring rotational and translational acceleration for all six degrees of freedom of movement. Thus, as in the above embodiments, no matching of the sensor elements is necessary.

Figures 19(a) and 19(b) respectively illustrate a compressive-type rotational accelerometer 122 having two acceleration sensing elements incorporated onto a single piece of piezoelectric polymer film as in the above embodiments and its equivalent circuit. As shown, rotational accelerometer 122 is formed on a substrate 124 using a piezoelectric polymer film 126 connected to the substrate via segmented electrodes 128 and 130. The side of the polymer film 126 opposite the segmented electrodes 128 and 130 includes a common electrode 132 which has a mass 134 placed thereon to "compress" the piezoelectric polymer film 126 so as to induce an output. The mass 134 actually comprises two separate masses separated by a distance δ so as to provide pyroelectric rejection in the piezoelectric film 126 in accordance with techniques known to those skilled in the art. By configuring the electrodes as indicated, the signal subtraction for the two sensor elements is accomplished directly on the sensor elements.

Figure 19(b) illustrates the equivalent circuit of Figure 19(a) where the transducer element 126 is designated 126a and 126b for the parts thereof at the two free ends, with the indicated polarities. As indicated, the induced output signals pass through an effective resistance 136 and are amplified by amplifier 138 for processing. Those skilled in the art will appreciate that the embodiment of Figure 19 has a sensitivity to linear acceleration, base strain and pyroelectric properties which is approximately zero, while the angular sensitivity is controlled by δ, which is in turn controllable during manufacture. Those skilled in the art will also appreciate that since the same piece of piezoelectric film is used for both linear accelerometers of the rotational
accelerometer, a good CMRR may be obtained with a very simple design.

Figure 20 illustrates a compressive-type linear accelerometer similar to the embodiment of Figure 19 except that mass 134 is replaced by mass 140 over one segment of the electrode (electrode 130). As will be appreciated by those skilled in the art, the accelerometer of Figure 20 is sensitive to linear acceleration only since the base strain and pyroelectric sensitivity are approximately zero if the mass 140 is properly placed on the piezoelectric polymer film 126. Due to the imbalance in stress applied to the polymer film 126 adjacent electrodes 128 and 130, common mode rejection for angular acceleration measurement is not obtained.

Figure 21 illustrates an equivalent circuit for a combined rotational and linear accelerometer designed by combining the embodiments of Figures 19 and 20. As illustrated, trimming capacitors 142 and 144 may be used to adjust the sensitivities of the individual transducers at differential amplifier 146 to improve CMRR, while the trimming resistor 148 may be used to adjust the overall transducer sensitivity.

Figures 22(a) - 22(c) respectively illustrate alternative configurations for an angular accelerometer and their equivalent circuit in accordance with the third embodiment of the invention. In this configuration, only a single ended electronic amplifier is needed which eliminates the requirement for a differential amplifier. As shown, the sensor is formed on rigid substrate 150 by placing piezoelectric polymer film 152 between segmented electrodes 154 and 156 on one side and common electrode 158 on the other side. In Figure 22(a) mass 160 is placed on common electrode 158 as in the embodiments of Figures 19 and 20 to impart necessary stresses into the piezoelectric film 152 during periods of acceleration, whereby all motion stimuli is applied through the substrate 150. In Figure 22(b), on the other hand, the electrode pattern is reversed between the substrate 150 and the mass 160. In Figure 22(b), if the mass 160 is a conductive
material, then an insulator 164 must be interposed between the mass 160 and the surface of electrodes 154 and 156 to prevent shorting. The output of electrode 156 in this configuration is a voltage which is proportional to the angular acceleration, and this voltage is amplified by amplifier 162 before further signal processing. The equivalent electrical circuit for this embodiment is illustrated in Figure 22(c).

The segmented electrodes 154 and 156 together with common electrode 158 thus form two angular accelerometers on a single piece of piezoelectric film 152. Preferably, the resulting accelerometer sensors are connected out of phase and in series to provide the common mode rejection for eliminating the sensitivity to linear acceleration, temperature transients, transverse acceleration, and base strain. In this embodiment, the angular acceleration is sensed by a single sensor element rather than two physically separate accelerometers, and common mode rejection of unwanted stimuli is inherent in the series opposed connection of the adjacent sensor portions of the single sensor element. Moreover, the effects of transient temperature, linear acceleration, transverse acceleration and base strain are cancelled. This simple configuration also does not require matching the amplitude responses, frequency responses, phase responses and dynamic ranges of the sensor outputs as in prior art configurations.

Figures 23(a) - 23(c) illustrate an alternative way to connect the sensor pair of Figure 22 to an electronic circuit to form an angular accelerometer. This alternate configuration connects the sensors which are in parallel and in phase to the inputs of a differential amplifier 166. The basic configuration of the sensor pair element is otherwise the same as in Figure 22. However, in Figure 23(a), rather than the signal subtraction occurring on the sensor pair, the signal subtraction occurs in the differential amplifier 166. This configuration is advantageous when it is convenient to connect the common electrode to ground rather than either of the segmented electrodes 154 and 156. Figure 23(b) illustrates that the electrode pattern also can be turned upside-down
between the substrate 150 and the mass 160 without affecting operation. Figure 22(c) illustrates the equivalent circuit for this parallel configuration.

The angular accelerometer described in accordance with the third embodiment will achieve optimum performance when it has the proper mounting orientation. This orientation typically can be found by placing a point at the physical center of each sensor element. These points must lie on a line that is emanating radially from and perpendicularly to the line describing the center of rotation about which the angular acceleration is to be sensed. The surface of the substrate 150 opposite the sensor elements is considered to be the mounting surface of the accelerometer and all motion stimuli are applied through the substrate 150. During angular acceleration, each sensor element will undergo either a compression or tension as imparted by the mass 160 attached to the top surface. Each sensor element will then output a charge signal that is proportional to and of the correct polarity describing the stress imparted by mass 160. In a properly mounted accelerometer in accordance with the third embodiment of the invention, the angular acceleration produces signals of unequal value in the respective sensor elements. Because the configuration subtracts one signal from the other, an output signal proportional to the amplitude of the angular acceleration will be produced, while for linear and transverse acceleration, temperature transients, and base strain, the signals produced from the sensor elements are of equal value so that when signal subtraction occurs, the resultant output is zero.

Although exemplary embodiments of the invention have been described in detail above, those skilled in the art will readily appreciate that many additional modifications are possible in the exemplary embodiments without materially departing from the novel teachings and advantages of the invention. Accordingly, all such modifications are intended to be included within the scope of this invention as defined in the following claims.
WHAT IS CLAIMED IS:

1. A multi-mode accelerometer for sensing the acceleration in at least one angular direction of movement of an object, comprising:
   a substantially flat, elongated beam structure comprising a piezoelectric film transducer which produces electrical signals proportional to its deflection, a common electrode on a first side of said piezoelectric film transducer, and first and second electrodes on a second side of said piezoelectric film transducer which is opposite said first side, said first and second electrodes being electrically isolated from each other; and
   a support structure for supporting said elongated beam structure at a mid-section thereof, whereby end portions of said elongated beam structure on either side of said mid-section deflect in opposite directions in response to angular movement of said elongated beam structure in said at least one angular direction.

2. An accelerometer as in claim 1, wherein said common electrode comprises a rigid conductive beam.

3. An accelerometer as in claim 2, wherein said support structure comprises three conductive elements which respectively contact said common electrode and said first and second electrodes so as to form electrical contact therewith and to support said beam structure with respect to said object.

4. An accelerometer as in claim 1, wherein said beam structure further comprises a nonconductive beam for supporting said piezoelectric film transducer and said common, first and second electrodes.

5. An accelerometer as in claim 4, wherein said nonconductive beam comprises a central notch through which said piezoelectric film transducer passes such that one end of said
piezoelectric film transducer is on one side of said nonconductive beam and another end of said piezoelectric film transducer is on another side of said nonconductive beam.

6. An accelerometer as in claim 5, wherein said first and second electrodes have tab portions and said support structure includes a printed circuit board having slots for accepting said tabs.

7. An accelerometer as in claim 4, wherein said piezoelectric film transducer is spot poled in opposite polarities at opposite end portions thereof.

8. An accelerometer as in claim 1, wherein said object is a read/write head of a computer disk drive and said electrical signals provide a read/write interrupt to said computer disk drive when acceleration above a predetermined threshold in said at least one angular direction of movement is sensed.

9. A multi-mode accelerometer for sensing the acceleration of an object along X, Y and Z axes comprising an accelerometer for each of said axes, each accelerometer comprising:
   a substantially flat, elongated beam structure comprising a piezoelectric film transducer which produces electrical signals proportional to its deflection, a common electrode on a first side of said piezoelectric film transducer, and first and second electrodes on a second side of said piezoelectric film transducer which is opposite said first side, said first and second electrodes being electrically isolated from each other; and
   a support structure for supporting said elongated beam structure at a mid-section thereof, whereby end portions of said elongated beam structure on either side of said mid-section deflect in opposite directions in response to angular
movement of said elongated beam structure in said at least one angular direction.

10. An accelerometer as in claim 9, wherein said object is a read/write head of a computer disk drive and said electrical signals provide a read/write interrupt to said computer disk drive when acceleration above a predetermined threshold along at least one of said X, Y and Z axes is sensed.

11. A multi-mode accelerometer for sensing the acceleration in at least first and second angular directions of movement of an object, comprising:
   a piezoelectric sensor comprising a thin conductive sheet laminated on one side thereof to a piezoelectric film transducer which produces electrical signals proportional to its deflection, said conductive sheet functioning as a common electrode and a structural support on a first side of said piezoelectric film transducer, and first and second electrodes on a second side of said piezoelectric film transducer which is opposite said first side, said first and second electrodes being electrically isolated from each other,
   whereby said piezoelectric transducer has a first portion thereof which includes a first substantially flat, elongated beam structure which is supported at a mid-section thereof so as to deflect in opposite directions at end portions thereof on either side of said mid-section in response to angular movement of said first elongated beam structure in said first angular direction and a second portion thereof which includes a second substantially flat, elongated beam structure which is connected at a mid-section thereof to said object and has free ends on either side of said mid-section which are at respective angles to said object so as to deflect in opposite directions in response to angular movement of said second elongated beam structure in said second angular direction; and
   a support structure for connecting said second elongated beam structure at said mid-section thereof to said
object so as to allow deflection is said first and second angular directions in response to movement of said object.

12. An accelerometer as in claim 11, wherein said piezoelectric transducer has a third portion thereof which includes a third substantially flat, elongated beam structure which is supported at a mid-section thereof so as to deflect in opposite directions at end portions thereof on either side of said mid-section in response to angular movement of said third elongated beam structure in a third angular direction.

13. An accelerometer as in claim 11, wherein said object is a read/write head of a computer disk drive and said electrical signals provide a read/write interrupt to said computer disk drive when acceleration above a predetermined threshold in at least one of said first and second angular directions of movement is sensed.

14. A multi-mode accelerometer for sensing the acceleration in at least one angular direction of movement of an object, comprising:
   a substrate;
   a piezoelectric film transducer disposed on a surface of said substrate, said piezoelectric film transducer comprising a piezoelectric film for producing electrical signals proportional to its deflection, a common electrode on a first side of said piezoelectric film, and first and second electrodes on a second side of said piezoelectric film which is opposite said first side, said first and second electrodes being electrically isolated from each other; and
   a mass attached to a side of said piezoelectric film transducer opposite said substrate for imparting stress to said piezoelectric film during acceleration in said at least one angular direction,
   whereby acceleration in said at least one angular direction is proportional to said stress applied to said piezoelectric film by said mass.
15. An accelerometer as in claim 14, wherein said mass comprises a first portion substantially centered over said first electrode and a second portion substantially centered over said second electrode so that it stress said piezoelectric film in response to angular acceleration in said at least one angular direction at a sensitivity functionally related to a distance between said first and second portions of said mass.

16. An accelerometer as in claim 14, wherein said mass is substantially centered over said first electrode so that it stresses said piezoelectric film in response to linear acceleration of said mass.

17. An accelerometer as in claim 14, further comprising an insulator between said first and second electrodes and said mass, whereby said first side of said piezoelectric film and said common electrode are disposed adjacent said substrate.

18. An accelerometer as in claim 17, further comprising an amplifier, wherein said first electrode is grounded and said electrical signals are applied to said amplifier via said second electrode.

19. An accelerometer as in claim 14, further comprising an amplifier, wherein said first electrode is grounded and said electrical signals are applied to said amplifier via said second electrode.

20. An accelerometer as in claim 17, further comprising a differential amplifier connected at respective inputs thereof to said first and second electrodes.

21. An accelerometer as in claim 14, further comprising a differential amplifier connected at respective inputs thereof to said first and second electrodes.
22. An accelerometer as in claim 14, wherein said object is a read/write head of a computer disk drive and said electrical signals provide a read/write interrupt to said computer disk drive when acceleration above a predetermined threshold in said at least one angular direction of movement is sensed.
**Fig. 1**

**Fig. 2**

**Fig. 3**

SUBSTITUTE SHEET
INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER
IPC(5) : G01F 1/00
US CL : 73/513
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED
Minimum documentation searched (classification system followed by classification symbols)
U.S. : 310/328,329,330,333,328,366; 73/DIG. 4

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic database consulted during the international search (name of database and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

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<th>Citation of document, with indication, where appropriate, of the relevant passages</th>
<th>Relevant to claim No.</th>
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<td>Y,P</td>
<td>JP, A, 4-20865 (INANAGA) 24 January 1992, See abstract.</td>
<td>1-4, 8-10</td>
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[X] Further documents are listed in the continuation of Box C. See patent family annex.

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be part of particular relevance
"E" earlier document published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"Z" document member of the same patent family

Date of the actual completion of the international search: 05 MARCH 1992
Date of mailing of the international search report: 24 MAR 1993

Name and mailing address of the ISA/US Commissioner of Patents and Trademarks
Box PCT
Washington, D.C. 20231
Facsimile No. NOT APPLICABLE

Authorized officer: MICHAEL J. BROCK
Telephone No. (703) 305-4922

Form PCT/ISA/210 (second sheet)(July 1992)
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<td>This international search has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:</td>
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<td>1. ☐ Claims Nos.:</td>
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<td>because they relate to subject matter not required to be searched by this Authority, namely:</td>
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<td>2. ☑ Claims Nos.: 11-13</td>
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<td>because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:</td>
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<td>3. ☐ Claims Nos.:</td>
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<td>because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).</td>
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<td>This International Searching Authority found multiple inventions in this international application, as follows:</td>
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<tr>
<td>1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.</td>
</tr>
<tr>
<td>2. ☐ As all searchable claims could be searched without effort justifying an additional fee, this Authority did not invite payment of any additional fee.</td>
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<td>3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:</td>
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<tr>
<td>4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:</td>
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<td>☐ The additional search fees were accompanied by the applicant's protest.</td>
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2. Where no meaningful search could be carried out, specifically:

Claims 11-13 recite a transducer with 2 or 3 "beam structures" but only 1 common electrode, a pair of secondary electrodes on the opposite side of a piezoelectric sheet. It is not understood how 2 or 3 "beam structures" could operate with only 2 secondary electrodes nor is there support from the disclosure to explain the claimed invention.