

Description

BACKGROUND OF THE INVENTION

Field of the Invention

This invention relates generally to transducers which may be fabricated from semi-conductor material such as silicon by batch photolithographic techniques from a monocrystalline wafer. More particularly, the invention relates to a spring-mass-support structure for detecting a signal proportional to acceleration applied to the support structure. The invention also relates to electronic circuitry in combination with the structure for detecting displacement of the spring supported mass to produce analog or binary representations of acceleration applied to the support structure.

Description of the Prior Art

A publication by Kurt E. Petersen entitled "Silicon as a Mechanical Material" published in Vol. 70, No. 5 (May, 1982) of the Proceedings of the IEEE, surveys the art of micro-machining of silicon to fabricate a mechanical device. The Petersen publication describes etching techniques commonly used in fabricating micromechanical devices and describes several devices which have been made using such techniques. The publication also describes a cantilever beam light modulator array the beams of which are fabricated of silicon dioxide. Another survey article appeared in the April, 1983 publication of Scientific American entitled, Silicon Micromechanical Devices by Angell, et al.

An accelerometer having a micromachined cantilever beam intended for in vivo biomedical studies and which includes a piezoresistive sensing element is described in a publication entitled, "A Batch-Fabricated Silicon Accelerometer" by Roylance and Angell in IEEE Transactions on Electron Devices, Vol. ED-26, No. 12, December, 1979.

U.S. patent Re.31,459 (reissue of U.S. patent No. 4,071,838) reissued December 6, 1983 in the name of Barry Block discloses a silicon folded leaf spring force transducer fabricated by batch photolithographic and etching techniques. One embodiment of such transducer consists of four E-springs located at 90° angles about the central axis of sensitivity. Piezoresistors disposed on legs of the E-springs provide a measure of the displacement of the springs in response to a force applied to the transducer.

U.S. patent 4,155,516 issued March 13, 1979, in the name of Harry Aine discloses first and second leaf spring structures, as supported from support structures, which are coupled together in axially spaced mutually opposed relation so that the first and second leaf spring structures are coupled together for deflec-

tion in unison relative to the surrounding support structures in response to deflection of either of the first and second spring structures. A capacitive detector structure is provided for detecting displacement of the leaf spring.

U.S. patent 4,597,003 issued June 24, 1986, in the names of Aine and Block discloses a method of chemical etching a silicon wafer by undercutting an etch stopped layer to fabricate a cantilever beam supported at one end by a frame structure with an integral mass formed by the etch. Etching from opposite etch stopped layers of a silicon wafer is described.

A force measuring apparatus in which a pulsed voltage is used to create a balanced electrostatic force in response to the signals of a displacement sensor is known from US-A-3 911 738.

While the art described above has advanced the art of micro-machining of silicon wafers to fabricate sensors in general and accelerometers in particular, there remains a need for a micro-machined structure of silicon and other materials and associated electronics meeting extremely precise specifications. For example, extremely low distortion for an accelerometer is required for certain applications. Prior art spring configurations and materials are believed to produce spring constants which change unacceptably over a deflection range of interest. Very low sensitivity to accelerations orthogonal to the sensitivity axis is desired. Prior art spring mass configurations do not provide sufficient insensitivity to orthogonal acceleration and angular motion applied to such configurations. Very high dynamic range (requiring extremely low noise) is desired in an accelerometer which has not been provided by prior art accelerometers and associated detecting electronics systems. Shock impact insensitivity is required in an accelerometer intended for use in certain applications such as in the seismic, automotive, or aeronautics fields.

An application normally requiring a high dynamic range is where it is necessary to measure small high frequency accelerations in the presence of large slowly varying accelerations. In the present invention this is achieved by means of the arrangement as described in the amended claims.

BRIEF DESCRIPTION OF THE DRAWINGS

The objects, advantages and features of the invention will become more apparent by reference to the drawings which are appended hereto and wherein like numerals indicate like parts and wherein an illustrative embodiment of the invention is shown, of which:

Figure 1 is a transverse sectional view of a wafer of monocrystalline material from which a spring mass system is to be fabricated according to micro-machining techniques;

Figure 2 is a view similar to that of Figure 1 show-

ing an oxide layer formed on opposite sides of the wafer;

Figure 3 is a plan view of the wafer of Figure 2 showing areas for which spring-mass-structures will be fabricated;

Figure 4A is an enlarged view of an area of Figure 3 as indicated by line 4A of Figure 3 which indicates the orientation of the crystal top and bottom surfaces and its relation to (111) planes of the crystal;

Figure 4B is a sectional view of the wafer showing a part of the layout taken along the lines 4B-4B of Figure 4A with photo-resist material having been applied to the opposite sides of the wafer; Figures 5A and 5B are similar to Figures 4A and 4B but show a wafer portion after it has been masked with a pattern of a spring-mass-support structure, and after portions of the oxide layers have been removed, leaving a pattern of oxide partially defining ultimate etching openings on the opposite sides of the wafer;

Figures 6A and 6B are similar to Figures 5A and 5B but reflect further processing after etch stop material has been diffused into the crystal of the wafer on opposite surfaces in areas other than the etching openings and spring legs;

Figures 7A and 7B are similar to Figures 6A and 6B but reflect further processing after opposite wafer surfaces have been masked to allow further etch stop layer material onto wafer surfaces where surrounding support structure, central mass and bases of E-springs are patterned;

Figures 8A and 8B are similar to Figures 7A and 7B but reflect further processing after the etching openings on both sides of the wafer have had oxide previously covering them removed and show a relatively thick layer of silicon dioxide material having been grown over areas of the sides of the wafer defining E-spring legs;

Figure 9A shows a plan view of the one-half of the wafer after chemical etching of the wafer through etch openings has etched to (111) planes of the crystal of the wafer thereby undercutting the E-spring structures and severing the mass portion of the structure from the support portion while suspending the mass from the support and after further processing where the thin layer of etch stop material beneath oxide sides of the springs have been removed;

Figure 9B is a sectional view of the wafer illustrated in Figure 9A taken along section lines 9B-9B;

Figure 10 is a perspective view of the sensing element structure including support, E-springs and sensing mass, the view being partially cut-away to illustrate the central mass severed from the support structure to show the oxide springs and undercut etch stop layers of the mass, springs and support structure;

Figure 11 illustrates a cross-section through the sensing element showing the sensing mass supported by springs to undercut portions of the support member where gravity forces the mass to be disposed beneath the top plane of the support member, the view further showing a composite structure including top and bottom plates having force and sense conducting areas deposited on their faces corresponding to similar force and sense conducting areas on opposite surfaces of the sensing mass;

Figure 12 is a plan view of the sensing structure illustrating deposited conducting leads to the force and sense conducting areas of the mass surface from the support structure via the E-spring leads;

Figure 13 is a schematic illustration of an electrostatic feedback control system for detecting acceleration applied to the support system by substantially maintaining the sensing mass at a predetermined position between the opposite plates of the composite structure, the output of the system being an analog signal proportional to applied acceleration;

Figure 14 shows a schematic illustration of a system similar to that of Figure 13 but having an alternating voltage applied to the covering plate force and sense conducting areas, with a demodulator provided to develop an analog signal proportional to applied acceleration;

Figure 15 is a schematic illustration of a charge generator circuit used directly or with modification in the transducer systems of Figures 13, 14 and 16, 17, 18 and 19;

Figure 16 is a schematic illustration of a transducer having a binary bit stream output representative of the displacement or acceleration of a mass in a mass-spring-support structure with binary bit stream voltages applied to top and bottom force plates and with a constant charge applied to force plates of the mass with the result that a binary force is applied to the mass tending to restore it to its reference position;

Figure 16A is an illustration of a binary sampler used in the embodiments of Figures 16, 17, 18 and 19;

Figure 17 is similar to the transducer of Figure 16 except that a binary bit stream of charge is applied to the force plates of the mass and a constant electric field is applied across the force plates of the top and bottom plates;

Figure 18 is similar to the transducer of Figure 17 except that an electric field applied to the force plates of the top and bottom plates is modulated with an a.c. signal, and consequently the binary bit stream of charge applied to the force plates of the mass is also modulated;

Figure 19 is similar to the transducer of Figure 18

except that the charge applied to the force plates of the mass is modulated and modulated bit streams of the output signal are fed back to the force plates of the top and bottom plates;

Figures 20A-20C illustrate an application of the transducer of the invention used to measure acceleration on a submerged platform subject to tilt caused by wave and current action of the water; Figure 21 is a plan view of the mass and spring members of the sensing element of the transducer modified to include a gimbal force plate on the mass;

Figure 22 is a vertical cross-section through the sensing element illustrating sense, force, and gimbal force conducting areas on the mass and corresponding conducting areas on plates attached to a supporting member and which face the conducting areas on the mass;

Figure 23 is a schematic diagram of an accelerometer embody in the invention, showing two feedback loops for maintaining the mass of the sensing element at a position between opposing facing plates above and below the mass, where a low frequency loop is responsive to slowly varying gravitational acceleration due to the tilt of a platform on which the sensor is placed and a high frequency loop is responsive to high frequency accelerations;

Figure 24 is a schematic diagram of an accelerometer similar to that of Figure 23 but with an alternative technique for applying electrostatic feedback forces to the mass;

Figures 25A and 25B are schematic diagrams showing the frequency characteristics of a low pass filter and a high pass filter used in the embodiments of the accelerometers of Figures 23 and 24; and

Figure 26 is a block diagram of a digital computer used in conjunction with x and y accelerometers mounted on a submerged platform, such diagram illustrating computations for correcting measured accelerations for the effect of tilt of the platform in the water.

DESCRIPTION OF THE INVENTION

Two important motivating factors, among others, led to the accelerometer of this invention. The first is low manufacturing cost so that the resulting accelerometer may find wide application where many force sensing transducers are required. The second is an accelerometer having extremely high performance characteristics: wide dynamic range; low distortion; low sensitivity to motion orthogonal its sensitivity axis; and resistance to high shock impact. These requirements lead to the fabrication of the accelerometer by micro-machining techniques from a monocrystalline material such as silicon.

In the description that follows, Figures 20-26 only show arrangements embodying the present invention. Figures 1-19 and their description are included as background information.

Referring now to Figure 1, a typical wafer 10 is shown from which a batch of accelerometers are to be fabricated according to the process of the invention. In a typical example, the wafer 10 is made of a non-metallic monocrystalline material such as silicon, germanium, quartz, gallium arsenide, gallium phosphide, etc. In a preferred embodiment, the wafer 10 is made of a diamond cubic material, such as silicon. The wafer 10 has a thickness of about 500 microns, has polished top and bottom surfaces 12, 14 and has a convenient diameter, such as 3 to 8 inches. In the case of diamond cubic material, the crystallographic plane (100) is preferably formed at the upper 12 and lower 14 major surfaces of the wafer 10. Furthermore, the wafer 10, in the case of silicon, is preferably doped with a P type dopant to a conductivity of between 0.1 - 10.0 ohm-cm.

In the next step of the process, the wafer 10 is oxidized on opposite sides to form oxidized layers 16, 18 of 2500 angstroms in thickness as illustrated in Figure 2. This is conveniently achieved by putting the wafers in a furnace at 1100° C, in the presence of oxygen. Next, the oxide layers 16, 18 are each coated with a photoresist material such as KMER.

Figure 3 is a plan view of the wafer with multiple areas each of which are to be processed simultaneously to batch produce the mass-spring-support structures. One particular area is illustrated in Figure 3 with line 4A-4A, shown much enlarged in Figure 4A. The boundary edges 24 of the structure to be fabricated are oriented parallel to the (111) planes of the crystal as illustrated in Figure 4A. Each structure of the array of structures of Figure 3 will ultimately be cut along the boundary edges 24 parallel to the (111) planes of the crystal after batch processing. Figure 4B shows a cross-section through a portion of the wafer showing the KMER photoresist layers 20, 22 deposited over silicon dioxide layers 16, 18.

Figure 5A shows one side of the wafer (for convenience called here the top side) after masking and exposure of the pattern as depicted thereon. The unexposed photoresist portion covers the etch opening patterns 30' and the spring legs 30", but the remainder of the photoresist portions are removed by exposure and development of the photoresist. The wafer is then placed in a silicon oxide etch solution such as buffered hydrofluoric acid, which attacks the oxide but not the photoresist or the underlying silicon. The photoresist protects the pattern 30 as illustrated in Figure 5A. The pattern 30 includes two parts: the regions indicated by 30' will ultimately be etch openings; the regions marked 30" will ultimately be spring legs. Figure 5B shows a cross-section through lines 5B-5B of Figure 5A and illustrates the oxide portions

30' and 30" on top and bottom surfaces 12, 14 which respectively ultimately form a slot opening behind the base of the E-spring and the middle leg of the E-spring. Oxide portions 30' and 30" are greatly enlarged in Figure 5B for ease of illustration.

The oxide pattern 30' of Figures 5A and 5B will ultimately serve as the etch openings to fabricate the three dimensional mass-spring-support structure of the accelerometer. The oxide patterns of 30" will ultimately be the location of the spring legs of the E-springs. A perspective view of the structure may be seen in cut-away sectional view of Figure 10 showing the structure at a certain stage in the processing.

Figure 5A illustrates particular features of the grown oxide patterns 30' and 30" which ultimately will result in the structure of Figure 10. The lines 32-32 of Figure 5A show a region in which an "E"-shaped spring 40 will be fabricated to partially support a mass 36 from a surrounding support structure 38. The E-spring 40 will include a base 42 and three legs 44, 46, 48. Slots or openings 43, 45, 47 will ultimately outline the shape of the E-spring. The inner leg 46 is twice the width of outer legs 44, 48. The lengths of the legs 44, 46, 48 are precisely the same.

Each E-shaped spring 40 is placed at the corner of intersecting (111) planes, that is, at 45° angles to intersecting lines of (111) planes which intersect the surfaces 12, 14 of the mono-crystalline wafer 10. The base 42 of each spring will ultimately be fabricated of stiff etch stop material while each leg 44, 46, 48 will ultimately be fabricated of silicon dioxide, as described below in more detail.

Two characteristics of the shape of the pattern of lines 32-32 are important. The first relates to the area identified by arrow 50, which connects the inner leg 46 to the sensing mass 36. Solely for purposes of illustration and description, this region is called the "cat head with ears" region, and is pointed to by reference arrow 50. The top of the cat head is attached to inner leg 46 with its "neck" or "body" attached to mass region 36. The "ears" of the cat head and ears region extend into oxide areas which ultimately will be openings between sensing mass region 36 and support region 38. The cat head and ears geometry provides a stiff region of mass 36, ultimately to be fabricated of undercut etch-stop material, to which inner leg 46 is connected.

The second shape relates to an area pointed to by reference arrow 52 of Figure 5A. Solely for purposes of illustration and designation, this region is called the "hockey stick" region because of its general resemblance to the shape of a hockey stick. This hockey stick region, ultimately to be undercut etch stopped material between regions 43 and 56 (which ultimately will be openings formed by means of silicon etching), provides a relatively wide region at the top of the foot of the hockey stick by which outer leg 44 (or 48) attaches to etch stopped material. Such wide region

provides a strong connection between the ends of the outer legs of the E-springs and the etch stopped material of the surrounding support structure.

The oxide areas 56 (which ultimately will be openings) have edges 58, 60 which are coexistent with intersecting lines of (111) planes of the crystal with the (100) surface 12 of the wafer. These areas 56 serve as "etch-time and undercut control" areas and are given the short-hand notation, "ETUC" areas. They ultimately serve as large open areas by which etchant chemical will undercut E-springs 40. Their area must be relatively large to allow etchant to etch to intersect (111) planes having intersecting lines 62, 64 with the surface 12. Areas 56 must be large enough to speed the etching process to completion to the intersection of the planes of the intersecting lines 62, 64, but must be shaped as shown to provide the "hockey stick" etch stopped areas 52 on its sides as discussed above. The inner edge 60 defines the intersecting line of a (111) plane of the crystal which will define the outer surfaces of the mass region 36.

Another factor dictating the shape of ETUC areas 56 is the requirement that during chemical etching, the mass region 36 must be severed from the surrounding support frame 38. Chemical etching of the silicon wafer occurs in one direction along (111) planes which intersect with lines such as 64 and 62 of the top and bottom surfaces which are extensions of edges 58 of ETUC areas. Chemical etching of the silicon wafer occurs in the opposite direction along (111) planes which intersect lines which extend from inner edges 60 of the ETUC areas of the top and bottom surfaces. When the etching from the opposite directions along (111) planes meet, the mass 36 is separated from support frame 38 as can be seen in Figure 9B. Consequently, the distance between edges 58 and 60 must be great enough to allow the mass region 36 to be separated from support frame 36 during chemical etching.

Turning now to Figure 6A, the silicon dioxide regions 30' defining openings of Figure 5A and the spring leg regions 30" are masked, and the uncovered silicon portions are implanted with a thin layer of arsenic. The arsenic is diffused a short distance, (6 to 7 microns) in the silicon to form N⁻ layers on top and bottom surfaces that are used as electrochemical etch stop layers in the silicon crystal. This stage of the processing is illustrated in the cross-section of Figure 6B. Next, the oxide of spring leg region 30" (of legs 44, 46, 48) is removed and an additional two micron thickness of arsenic is diffused into the silicon. Figure 7B shows this stage of the processing. The thickness of the etch stop layer 70' is now about 8-9 microns thick.

In preferred processing of the mass-spring-support structure, the thick layer of arsenic is especially important to impart stiffness to certain regions of the top and bottom etch stop layers. The base of

the springs 42, cat head region 50 and the hockey stick region 52 require stiffness and strength to connect with the spring legs 44, 46, 48 so that the mass region 36 may be adequately supported from support region 38.

Figures 8A and 8B show the condition of the wafer after the silicon dioxide regions 30' have been stripped from the wafer 10, a thick layer (1.2 microns) of silicon dioxide has been regrown everywhere over top and bottom surfaces, and finally such silicon dioxide has been stripped away everywhere except over spring leg portions 44, 46 and 48. Silicon dioxide layer 30''' remains for such legs as is shown in Figure 8B. At this point in the processing, conductive areas are provided on the opposite faces of the mass region 36 and conductive leads running from the support region via the legs 48 or 44, 46 and base 42 are deposited. For simplification of illustration, the results of providing such conductive region and leads are illustrated in Figure 12 and described below.

Next, the wafer is subjected to electro-chemical etching such that the wafer is etched away from the ETUC areas 56 and other open areas, such as slots 43. The etch chemical etches beneath etch stop layer 70' preferentially along (111) planes of the crystal of the wafer. The preferred etching process is similar to that described in U.S. patent 4,597,003, described above and incorporated herein by reference for its electro-chemical etching methods. Next, the thin layers 70''' (Figures 7B, 8B) of etch stop material are removed by subjecting the wafer to a silicon etch (either dip or plasma) everywhere. Such etching causes etch stop layer 70' to be reduced in thickness by about 2 microns, that is, to an ultimate thickness of about 6-7 microns.

The result of the processing described above is a three dimensional support-spring-mass structure illustrated in plan and cross-section views of Figures 9A and 9B and the perspective view partially broken away of Figure 10. The etching process has etched the silicon material away, along the (111) planes defined by the intersection of such planes with lines parallel to edges 58, 60 of each of the ETUC areas 56. Undercut etch stop layers 70' are visible in Figures 9B and 10 as well as the suspended mass 36, surrounding support structure 38 and silicon dioxide spring layers 30'''. The bases 42 of the E-springs 40 are formed of undercut etch stop material 70' as seen in Figure 9B and 10.

An important feature is apparent from Figures 9A and 9B. That feature is the fact that bases 42 of the E-springs are fabricated of etch stop material 70' while the legs 44, 46, 48 of the E-springs are substantially entirely of silicon dioxide. This difference in materials allows the stiffness of the base of each E-spring to be substantially greater than that of the legs.

The coefficient of stiffness (Young's modulus) is approximately three times greater for silicon than it is

for silicon dioxide. The thickness of the base 42 at each E-spring is controlled during processing to be greater than seven times as thick as that of the silicon dioxide legs. The resulting stiffness of the base, consequently, is seven cubed times three, or more than 1000 times stiffer than the legs for similar lengths and widths of material.

Each spring leg 42, 46, 48 of each E-spring 40 is precisely the same length from its connection at one end of its respective base 42 to its respective connection to either the top of the foot of the hockey stick area or to the head of the "cat head with ears" area. It is fabricated of silicon dioxide, as described above, because the thickness of the silicon dioxide legs may be very accurately controlled. The length of each leg and its thickness must be accurately controlled so as to control the spring constant of the sensing member. It can be shown that the spring constant of the E-spring is proportional to the cube of the thickness of its legs. Another reason for fabricating the legs of each E-spring of silicon dioxide is that silicon dioxide is a well-behaved material in that it has no measurable hysteresis and it does not fatigue over many cycles of flexing.

Legs 44 and 48 are precisely the same width. Leg 46 is made up of one or more side by side legs whose composite width is precisely twice the width of legs 44 or 48. Although not illustrated, leg 46 is preferably a composite of three side by side legs, each leg of course having a smaller width than the composite width. Dividing the total width of leg 46 into three parts has been found to prevent buckling or crinkling of leg 46 after processing.

Figure 11 shows a cross-section of sensing element 80 sandwiched between opposite supporting members 82, 84. Sensing element 80 shows central mass 36 supported via spring legs 46, 48 and legs 46, 44 via bases 42 from surrounding support member 38. The mass 36 is shown displaced vertically by the force of gravity. The sense conducting areas 90 formed on opposite sides of the faces of mass 36 surround force conducting areas 92. Figure 12 shows a plan view of the support-spring-mass structure 80 with the force and sense conducting areas 92, 90 formed on the top face of the mass 36. Such areas 90, 92 are conductively isolated from each other. Although not shown in Figure 12 for simplification of illustration, guard regions are provided between areas 90, 92 to reduce the capacitive coupling between such areas. Corresponding force and sense conducting areas 92', 90' are provided on plate surfaces formed on opposite supporting members 82, 84. Such plate surfaces and force and sense conducting areas 92', 90' correspond in size and pattern to the opposite surfaces of mass 36 and its force and sense conducting areas 92, 90. Opposite supporting members are bonded to the support member 38 by conventional means.

Figure 12 shows conductors running from external connection pads to the force and sense plates. Such conductors are illustrated for one surface of the support-spring-mass structure 80 as an illustration of such conductors provided to the sense and force conducting areas of the top and bottom plates 82, 84 and the opposite surfaces of mass 36. Conductors 94 and 96, preferably gold, are deposited on opposite surfaces of the wafer and structure 80 such that they run respectively from connecting pads 98 and 100 via separate E-springs 40A and 40B. As illustrated, lead 94 connects to force conducting area 92 via legs 48 and 46 and base 42 of E-spring 40A, while lead 96 connects to sense conducting area 90 via legs 44 and 46 and base 42 of E-spring 40B.

The leads 94 and 96 respectively pass through tunnels 102, 104 provided for a seal (not shown) between sandwiched surfaces of support member 38 and opposite supporting members 82, 84. Conductor 94' is deposited on opposite leg 44 and a portion of base 42 of spring 40A to balance the weight and stiffness of conductor 94 on leg 48 and base 42. Likewise, conductor 96' is deposited on opposite leg 48 and a portion of base 42 of spring 40B to balance the weight and stiffness of conductor 96 on leg 44 and base 42. Conductor 94' is not electrically connected to conductor 94. Likewise, conductor 96' is not electrically connected to conductor 96.

Conductors 106 and 108 are deposited on E-springs 40C and 40D, but have no external electrical connection. Such conductors 106 and 108 provide weight and stiffness to springs 40D and 40C to balance the weight and stiffness of conductors deposited on springs 40A and 40B. Each of the four surfaces, two opposite faces of mass 36 and opposing surfaces of opposite support members 82 and 84, have similar conducting leads attached to their respective force and sense conducting areas. Such leads are connected to appropriate pads illustrated adjacent pads 98, 100 of Figure 12 which communicate with electronic circuitry described below.

Turning now to the electronic circuitry associated with the spring mass transducer described above, three alternative embodiments of transducer systems, or accelerometers, are illustrated respectively in Figures 13, 14 and 15. Figure 13 shows a mechanical schematic of the spring mass transducer of Figure 11.

Mass 36 is supported from a support 38 via springs 40 having substantially equal spring constants of 2ks. A d.c. voltage of magnitude V_{cc} is applied between sense conducting areas 90' on plates of opposite support members 82, 84, which of course are fixed with support 38. A d.c. voltage of magnitude V_{qq} (which may be the same as or different from magnitude V_{cc}) is applied between force conducting areas 92'. Leads 96 connected to top and bottom sense conducting areas 90 of mass 36 are connected to lead

110. Leads 94 connected to top and bottom force conducting areas 92 of mass 36 are connected to lead 112.

A differential amplifier 120 has one of its two inputs connected to lead 110 with another of its leads connected to a reference voltage which is provided with some fraction of magnitude V_{cc} , preferably, one half V_{cc} . The voltage appearing on lead 110 is proportional to the position of mass element 36 between the plates of support members 82 and 84, because a sense electric field is created between sense conducting plates 90' by voltage V_{cc} , and because sense conducting plates 90 of mass 36 are disposed in the path of that sense electric field. When the mass element 36 moves toward the plate of top support member 82, the voltage on sense plates 90 and lead 110 approach the magnitude V_{cc} ; conversely, when the mass element 36 moves toward the plate of bottom support member 84, the voltage on sense plate 90 and lead 110 approaches zero or ground magnitude.

Consequently, with the reference voltage $V_{cc}/2$ applied to differential amplifier 120, its output on lead 122 is a sense displacement signal proportional to the distance that mass element 36 has moved from a reference position, halfway between the reference plate of supports 82, 84. The displacement signal produced on lead 122 is smoothed and filtered by filter circuitry 124, resulting in an output signal on lead 126.

The voltage V_{qq} applied between force conducting areas of plates of top and bottom support members 82, 84, creates a force electric field across the force conducting areas 92 of mass 36. A negative feedback circuit, labelled as charge generator 130 (described below and illustrated in Figure 15) produces an output on its output lead 112 in response to the output displacement signal from lead 128 to apply an amount and magnitude of electric charge on force conducting areas 92 to move the mass toward its reference position, preferably halfway between support members 82, 84. The force on mass 36 is proportional to the numerical product of the amount of charge deposited on plates 92 times the force electric field, provided the mass is maintained close to or at its reference position.

In other words, force or acceleration applied to support 38 causes displacement of the mass 36 via the springs 40. Displacement of the mass from a reference position is sensed as a displacement signal which causes a charge generator 130 to generate a charge which is applied to conducting areas 92 so as to drive the mass back to its reference position. Consequently, the difference between the sense displacement signal on lead 110 and the reference potential $V_{cc}/2$ applied to lead 111 is extremely small, yet the output displacement signal on lead 126 after amplification, and filtering of the output of differential amplifier 120 is representative of the displacement of mass 36 in response to acceleration applied to sup-

port 38.

As long as the frequency of applied acceleration is below the effective resonant frequency of the spring-mass-support transducer, displacement of the mass of the transducer is directly proportional to acceleration, and the system of Figure 13 can be described as an accelerometer. Consequently, the output voltage signal of lead 126 is an analog signal proportional to acceleration for acceleration frequencies below the effective resonant frequency of the transducer.

Figure 14 is a block diagram of an accelerometer similar to that of Figure 13 but has an alternating voltage, preferably a square wave, applied between sense conducting areas 90' and force conducting areas 92' of the plates of opposite support members 82, 84. Different amplitudes of the square waves may be applied to the force and conducting areas. A square wave train, labelled V_{o1} , is illustrated in Figure 14 representative of the alternating voltage applied to the force and sense conducting areas 92', 90' of the opposite plates. The frequency of the square wave-train is high compared to that of an illustration of the displacement of mass element 36 in response to acceleration applied to support 38. The voltage appearing on lead 110 is an amplitude modulated signal (suppressed carrier) representative of the displacement of mass 36 from a reference position.

The difference signal of differential amplifier 120 is applied to band pass filter 124 via lead 122 which results in a modulated displacement signal on lead 126. The charge generator circuit 130 produces modulated voltages to apply charge to force plates 92 of mass 36 in synchronism with the square wave voltage applied to force conducting areas 92' of opposite support members 82 and 84 to drive the mass to its reference position.

The voltage on lead 126 is applied to demodulator 134 along with V_{o1} and $\bar{V}_{o1}$ inputs to produce an analog voltage on lead 136 representative of acceleration applied to supports 38 of the transducer. The advantage of the carrier system of Figure 14, over the analog system of Figure 13, is that the mass displacement signal is shifted out of the base band of the acceleration signal to a higher carrier signal of the square wave train thereby minimizing 1/f noise and d.c. offset problems.

The charge generator 130 of Figure 13 is illustrated in detail in Figure 15. The voltage from the output of the system of Figure 13 is applied via lead 128 to charge generator 130. Two control signal voltages, ϕ_1 and ϕ_2 as illustrated in Figure 15, are used to control conduction of MOS transistor pairs Q_1, Q_2 and Q_3, Q_4 respectively. Control signal voltages ϕ_1 and ϕ_2 provide non-coincident turn on signals of a period which is small compared to the period T of the highest frequency acceleration input to the system.

Capacitor C_{REF} is disposed in the conduction path

of transistors Q_1 and Q_2 . Consequently when Q_1 and Q_2 are turned on by control voltage ϕ_1 , a charge is placed on C_{REF} proportional to the output voltage V_{out} on lead 128. A positive charge is placed on capacitor C_{REF} if the output voltage V_{out} is positive, and vice versa. After control voltage ϕ_1 is turned off, transistor Q_3 and Q_4 are turned on by control voltage ϕ_2 thereby placing the charge stored on capacitor C_{REF} across the inputs of very high gain operational amplifier 137. In response, the output of amplifier 137 changes in a direction that causes the charge stored on capacitor C_{REF} to discharge. Lead 112 is connected between force plates 92 of the mass 36 of the sensor. Consequently, the discharge path for the charge stored on capacitor C_{REF} is through the capacitance of the force electrodes 92 via lead 112. The charge on the reference capacitance C_{REF} is totally transferred to force electrodes 92.

As long as control voltage ϕ_1 is in the off condition, or the $\bar{\phi}_1$ signal is applied to transistor pair Q_7, Q_8 , voltages V_{gg} and ground are applied respectively to corresponding force plates 92' of the top and bottom support plates 82, 84. During the time when control signal ϕ_1 is positive and $\bar{\phi}_1$ is not present, transistor pair Q_5, Q_6 conduct and cause top and bottom pairs of plates 92' and 92 to be connected together, thereby equalizing charge on the respective plates.

The circuit 130 could be modified such that the voltage V_{gg} is constantly applied lead to Q_1 on lead 128 and the output signal from lead 126 is applied to transistor Q_7 . This causes a fixed value of charge to be applied to plates 92 while the voltage across plates 92' is equal to the output voltage on lead 126.

The circuit could also be modified such that positive and negative voltages are applied respectively to plates 92' (or 92 as indicated above) such that the electric field across plates 92' is the difference between the positive voltage and the negative voltage. Likewise, the voltage applied across capacitor C_{REF} may be a negative voltage rather than ground as illustrated. Such modification will be apparent to one of skill in the electronic design art.

The charge generator 130 of Figure 14 is similar to that illustrated in Figure 15 except that the control signal voltages ϕ_1 and ϕ_2 are in synchronism with the modulation signal V_{o1} .

Figures 16 through 19 illustrate different arrangements where a binary bit stream representation of the displacement of the mass 36 is fed back to the mass-spring-support structure to generate a binary force on the mass in a direction tending to restore the mass to its reference position.

Figure 16 illustrates a support 38-spring-mass 36 system which is similar to the d.c. system of Figure 13 in that a displacement signal on lead 110 is applied to a differential amplifier 120 having a reference potential $V_{01/2}$ applied to it corresponding to a reference position of mass 36 between support plates 82 and

84. A difference signal on lead 122 is applied to a filter 124. The output of filter 124 on lead 126 is then applied to a binary sampler 150 which is illustrated in Figure 16A. The filtered differential displacement signal on lead 126 is applied to a threshold circuit 160 which produces a "1" ("high") or "0" ("low") signal on lead 161 depending on whether the displacement signal on lead 126 is greater than or less than a voltage threshold signal applied to lead 159. Consequently, the signal on lead 161 is either a "1" or a "0".

The binary signal on lead 161 is applied to flip flop circuit 162 to which is applied a clock signal labeled T_{CLOCK} and which is illustrated in Figure 16. The flip flop circuit produces outputs on its Q and $\bar{Q}$ leads 164, 166 which is a binary stream of pulses, as illustrated in Figure 16.

When the signal on lead 161 is a "1", the binary stream on the Q output (lead 164) is a stream of "1" pulses each of the same period as the pulses of the T_{CLOCK} signal. Simultaneously, the $\bar{Q}$ output (lead 166) is a binary stream of "0" pulses each of the same period. The bit streams are reversed when the signal on lead 161 is a "0". The illustration of "1"s and "0"s shown in Figures 16, 17, 18 and 19 is an accurate representation of how this signal will appear for a sigma delta modulation encoder.

It is preferred that the accelerometer of Figure 16, as well as those of Figures 17-19, have very high noise reduction characteristics. In order to achieve such noise reduction Figure 16 and Figures 17-19 include one or more integrators in the forward loop. With such an integrator, for example in conjunction with filter 124, the filter-integrator 124 and binary sampler 150, with feedback of the output signal to the mass 36 to be summed with the input signal applied to support 38, is defined as a sigma-delta-modulation system. It is preferred to have a single integrator in the forward loop, thus achieving a first order sigma-delta-modulation system. Lower or higher order systems may find application with the invention of Figures 16-19. Sigma delta modulation systems are described in an IEEE publication, "Stability Analysis of High-Order Sigma-Delta Modulators", by Ardan and Paulos, CH 2255 - 8/86/0000-0715, 1986.

The output binary bit stream of a sigma delta modulation system is mostly alternating bit patterns with the density of "1"s versus "0"s being the representation of the acceleration input. In Figure 16, the voltage bit streams on leads 164 and 166 are applied to force conducting plates 92' of the top and bottom support members 82, 84.

A constant charge is applied to force conducting plates 92 of mass 36 via charge generator 130 and leads 112, 94. Consequently, the force electric field across the mass 36 is applied in a series of binary voltage pulses to the support member conducting plates to drive mass 36 to its reference position as determined by the d.c. reference potential $V_{01/2}$. The binary

bit stream applied to plates 92' reverses in polarity of its bit density as the displacement signal on lead 126 crosses the threshold voltage level applied to threshold circuit 160. Such reversal of polarity of the bit streams on leads 164, 166 causes the mass 36 to be driven in the opposite direction.

The charge generator circuit 130 is similar in construction to that illustrated in Figure 15 except that a constant voltage V is applied to lead 128 which causes a constant amount of charge to be applied to conducting plates 92 of mass 36.

The output of the transducer of Figure 16 on lead 168 is a serial binary bit stream of 0's or 1's representative of the displacement of the mass 36 with respect to a reference position as specified by the reference potential $V_{01/2}$ applied to amplifier 120. As discussed previously, displacement of the mass 36 is proportional to acceleration applied to support 38 of the mass 36 spring support 38 system.

Figure 17 is an alternative binary bit stream embodiment of the transducer, similar to the transducer of Figure 16, except that a d.c. potential difference $V_{01} - \bar{V}_{01}$ is applied across force conducting plates 92' of top and bottom plates 82, 84. The binary bit stream output from the Q output of binary sampler 150 is applied to lead 128 to charge generator 130, which in response, applies "1"s or "0"s of charge to force conducting plates 92 via leads 112 and 94. In other words, the embodiment of Figure 17 is the inverse arrangement of that of Figure 16 in that a constant voltage is applied to force plates 92' of the top and bottom plates, but binary charge proportional to displacement of the mass 36 (in response to acceleration applied to support 38) is applied to the force plates 92. As before, mass 36 is driven in a direction toward its reference position as determined by the voltage $(V_{01} - \bar{V}_{01})/2$ applied to amplifier 120. The output on lead 168, like that of Figure 16, is a serial binary bit stream proportional to acceleration applied to the support 38 of the transducer.

Figure 18 shows a binary bit stream output and feedback which is representative of displacement or acceleration applied to the transducer. The arrangement of Figure 18 is similar to the analog arrangement of Figure 14 in that it applies an a.c. carrier voltage (square wave) to modulate the force electric field on force plates 92' and to sense plates 90' of top and bottom supports 82, 84. The arrangement of Figure 18 is also similar to the binary output arrangement of Figure 17 in that a binary stream of charge pulses, (but in this arrangement modulated by the carrier signal V_{01}) is fed back to force plates 92 of mass 36 in response to the operation of digital sampler 150. Like in Figure 17, the digital sampler 150 produces a binary bit stream on lead 168, but modulated by signal V_{01} , representative of displacement signal 126. Charge generator 130 produces a modulated binary bit stream on leads 112 and 94 in response to voltage

bits applied on lead 128 from lead 168. The modulated bit stream on lead 168 is demodulated by demodulator 153 (in a similar fashion as the analog signal on lead 126 of Figure 14 is demodulated) to produce a binary bit stream on lead 170 representative of displacement or acceleration applied to the transducer.

Figure 19 is similar to Figure 18, but feeds a modulated binary bit stream of voltage pulses back to plates 92' of top and bottom support plates 82, 84 and applies modulated charge, but of constant magnitude, to force plates 92 of mass 36. The result, after demodulation of the modulated binary bit stream signal on lead 152 by demodulator 153 is a serial binary bit stream representation of the displacement or acceleration applied to the transducer system.

Application of Micro-Machined Accelerometer to determine direction of a source of sound waves in a body of water

One application of the micro-machined accelerometer based on the principles described above is described in Figures 20A, 20B, and 20C. Such figures schematically describe a system for determining the direction of a source of sound waves S in a body of water. It is known that sound waves in water produce acceleration forces in the water as the sound propagates in the water. Measurement of the components of acceleration produced by such sound wave allows determination of the vector from the location of measurement to the source of the sound.

Figure 20A illustrates an arrangement for measuring such sound direction including a buoy 1004 floating on the surface 1002 of the body of water 1000. A submerged platform 1006 is attached to the buoy 1004 by means of a cable 1008. Platform 1006 has two accelerometers A_x (reference number 1010) and A_y (reference number 1012) mounted on it along x and y platform axes which are perpendicular to a third z axis which is directed along the cable 1008 connected between platform 1006 and buoy 1004. The z axis is defined to be along the gravity axis between the buoy and the center of the earth. The accelerometers A_x , A_y measure accelerations applied to platform 1006, such as the accelerations a_x and a_y due to a sound source illustrated in Figure 20A.

Figure 20B illustrates platform 1006 tilted about the y axis. In this condition an x component of gravitational acceleration acts on the mass of the accelerometers. The angular tilt θ_x about the y axis can be determined by determining g_{xp} , the component of gravitational acceleration measured along the platform x axis. Since the gravitational vector g_z is known, θ_x , the angle of tilt about the y axis may be determined as,

$$\theta_x = \sin^{-1} \frac{g_{xp}}{g_z}$$

It follows that the acceleration due to sound

waves in the x direction as measured along the xp axis by accelerometer A_x is determined by,

$$a_x = \frac{a_{xp}}{\cos \theta_x}$$

Figure 20C illustrates platform 1006 tilted about the x axis. In this condition, a y component of gravitational acceleration acts on the mass of the accelerometer. The angular tilt θ_y about the x axis can be determined by determining g_{yp} , the component of gravitational acceleration along the platform y axis. Since the gravitational vector g_z is known, θ_y , the angle of tilt about the xp axis is determined as

$$\theta_y = \sin^{-1} \frac{g_{yp}}{g_z}$$

The acceleration due to sound waves in the y direction as measured along the yp axis by accelerometer A_y is determined by,

$$a_y = \frac{a_{yp}}{[\cos \theta_y]}$$

The tilting of platform 1006 moves slowly as compared to the frequency of accelerations a_y and a_x due to sound source S. Consequently, the transducer described previously in this specification is modified so as to have low frequency analog feedback loop, by which the gravitational acceleration sensed by the spring-mass system of the transducer due to tilt is determined, in addition to the sigma-delta loop at higher frequencies for precisely determining acceleration along a platform axis due to sound waves. This frequency separation of measuring acceleration along a platform axis depends upon the physical characteristics of two components of acceleration along a platform axis being measured. In the application described in Figures 20A-20C the frequency content of the accelerations due to the sound waves is much higher than the gravitational acceleration caused by tilt of the platform. This difference in frequency of the two components of the total acceleration applied to the accelerometer allows acceleration due to the sound source to be measured separately from gravitational acceleration and to be electronically compensated for the tilt of the platform. An important advantage of such separate measurements of the components of acceleration is the decrease of the required dynamic range of the measurement of acceleration due to the sound source. In other words, the sigma delta loop of the higher frequency measurement of acceleration due to the sound source need not include measurement of the gravitational acceleration due to tilt, resulting in a lower dynamic range required for the measurement of acceleration due to the sound source.

Figures 21 and 22 illustrated a modified transducer from that illustrated in Figures 12 and 11 by which an additional force plate, called "gimbal force" plate (reference number 922), is added to provide an additional feedback path by which the mass 36' is

maintained at a predetermined position between plates 82' and 84' by an additional or "gravitational" feedback loop. The sensor itself is next described followed by a description of alternative arrangements of feedback loops.

The transducer of Figures 21 and 22 are identical to that described in Figures 12 and 11 except that two force plates 920 (labeled FORCE) and 922 (labeled GIMBAL FORCE) (instead of one force plate 92 of Figure 12) are provided with conductive material on top and bottom surfaces of the silicon mass 36'. Such force conducting areas are electrically isolated from each other by non-conducting area 924. Conductor 108 is provided from a location external of the mass 36' and springs to the gimbal force area 922. Conductor 108 is illustrated for one surface of the support-spring-mass structure 80', but is also provided to the opposite parallel surface. Conductor 108, like conductors 94 and 96, preferably gold, is deposited on opposite surfaces of the wafer. It runs from connecting pad 99 via E-spring 40D by running along springs 44 and 46 via base 42. The lead 108 passes through tunnel 103 provided for a seal (not shown) between sandwiched surfaces of support member 38 and opposite supporting members 82' and 84'. Conductor 108' is deposited on opposite leg 48 and a portion of base 42 of spring 40D to balance the weight and stiffness of conductor 108 on leg 44 and base 42. Conductor 108' is not electrically connected to conductor 108.

As shown by Figure 22, the top and bottom plates 82', 84' which are secured to support member 38 have planar surfaces which face top and bottom planar surfaces of mass 36'. Such top and bottom plates 82', 84' have sense conducting material 90' deposited thereon which oppositely face the sense conducting material 90 on mass 36'. Such material 90' is formed in a substantially identical pattern as the sense 90 conducting material. Likewise, patterns 922' on top and bottom plates 82', 84' face substantially identical patterns 922 on mass 36' to form "gimbal force" opposing plates. Patterns 920' on top and bottom plates 82', 84' face substantially identical patterns 920 on mass 36' to form "force" opposing plates.

The spring mass system, together with frame top and bottom plates 82', 84', are vacuum sealed to the top and bottom connections to support member 38. A vacuum environment is provided between opposing faces of top and bottom plates 82', 84' and mass 36' to avoid non-linear viscous damping. Damping of the spring mass system subjected to an acceleration input is controlled electromechanically by the closed loop feedback system described below.

The top and bottom plates 82', 84' are fabricated of 500 micron thick silicon, such that they are thermally matched to the silicon of mass 36'. The gaps between the surfaces of mass 36' and the opposing surfaces of top and bottom plates 82', 84' are approxima-

tely 1.5 microns in distance.

Turning now to Figure 23, the spring mass sensor is connected in a first arrangement to ultimately determine acceleration applied to support 38 along an axis of sensitivity Z. Of course such axis of sensitivity may be oriented along any axis, such as illustrated in Figures 20A-20C where accelerometers according to the invention are placed on platform 1006 to be sensitive to x and y platform axes.

The schematic of Figure 23 shows that mass 36' is supported from support 38 via springs having substantially equal spring constants of 2ks. A d.c. voltage of plus V and minus V is applied across sense conducting areas 90' on plates of opposite support members 82', 84' which of course are fixed with support 38.

A differential amplifier 120 has one of its two inputs connected to lead 110 with another of its leads connected to a reference voltage, preferably ground. Lead 110 is connected to sense conducting surfaces 90 of mass 36'. The voltage appearing on lead 110 is proportional to the position of mass element 36' between the plates of support members 82' and 84'. Consequently with the ground reference applied to differential amplifier 120, its output on lead 112 is a sense displacement signal proportional to the distance that mass element 36' has moved from a reference position, halfway between the reference plate of supports 82, 84.

Two feedback loops are provided. The first includes a high pass filter 124', binary sampler loop with binary feedback to force support plates 920'. The second includes a low pass filter 924 with analog feedback to "gimbal force" support plates 922'. For each feedback loop, a constant charge is maintained on mass force plates 920 and mass gimbal force plates 922 via leads 94 and 95 from charge generators 130 and 131. Such generators are described above with reference to Figure 15.

The low pass filter 924 and high pass filter 124' are illustrated by way of their frequency responses in Figures 25A and 25B. The low frequency analog loop includes low-pass filter 924 which has a high frequency cut-off frequency of about .7HZ. Its response increases in attenuation at frequencies above such cut-off frequency at a rate of about 20db per increasing decade of frequency.

The delta-sigma binary bit stream loop includes high-pass filter 124' which has a low frequency cut-off frequency of about 700HZ at about 20db per decreasing decade of frequency. Its response decreases in attenuation at frequencies below about 700HZ. Filters 924 and 124' may be realized by filter circuitry well known in the art of analog filter design.

Returning to Figure 23, the displacement error signal after amplification and high pass filtering is applied on lead 126 to binary sampler 150 which produces a serial binary bit stream on lead 168. That bit

stream, representative of the displacement of mass 36' in response to acceleration, is applied via lead 164 to top support force plate 920', while the complementary binary bit stream on lead 166 is applied to bottom support force plate 920'. Such binary bit voltages applied to top and bottom force plates 920' and the constant charge applied to mass force plates 920 cause mass 36' to move in a direction to null the voltage or "V_{ERROR}" on lead 110. Such high frequency loop is effective at frequencies passed by filter 124'.

The low frequency loop responds to accelerations passed by filter 924. The displacement signals at such frequencies are filtered via filter 924 and applied via lead 926 to amplifier 928, where a voltage of opposite sign to the input voltage on lead 926 is applied via lead 930 to top support gimbal force plate 922' and a voltage of the same sign is applied via lead 932 to bottom support gimbal force plate 922'. Such analog voltages applied to top and bottom gimbal force plates 922' and the constant charge applied to mass gimbal force plates 920 cause mass 36' to move in a direction to null the voltage or "V_{ERROR}" on lead 110. Such low frequency loop is effective at low frequencies passed by filter 924.

As will be apparent to one of skill in the field of negative feedback or automatic feedback controls as applied to sensor design, each of the two feedback loops must be stable. Depending on the components used to implement the low frequency loop and the delta-sigma binary bit stream loop of Figure 23 (and of other loops presented herein), it may be advantageous to provide a lead compensator in one or both loops. A simple lead compensator may be combined with filter 124', for example in the binary loop, if a stability analysis of the loop so requires, of the form of a parallel resistor R₁ and capacitor C followed by a resistor R₂ to ground. The output/input relation G(S) of such a lead compensator, written in terms of Laplace transform operator S is of the form

$$G(S) = \frac{S + 1/T}{S + 1/\alpha T}$$

where $T = R_1 C$,

$$\alpha = R_2 / (R_1 + R_2).$$

When used in the application as illustrated in Figures 20A-20C, the accelerometer of Figure 23 effectively uses the low frequency analog feedback loop to separately measure the low frequency gravitational effects on platform 1006. Thus, the terms "electronic gimbal" and "gimbal" force plates are applicable. The high frequency feedback loop of the accelerometer measures high frequency accelerations along the x_p and y_p axes of platform 1006, independent of the gravitational acceleration caused by tilt. In effect, the platform is electronically gimbled (as if it were mechanically oriented to be perpendicular to the true gravity vector), to eliminate substantially the effect of tilt and gravity. Of course, the low frequency loop or elec-

tronic gimbal reduces the required dynamic range of the higher frequency measurement of accelerations due to a sound source.

Figure 26 illustrates other components of the system used in conjunction with accelerometers 1010 (accelerometer A_x) and accelerometer 1012 (accelerometer A_y) which are of the design of Figure 23 (or the alternative designs discussed previously or below). The output of the high frequency loop on lead 168' is a serial binary bit stream representative of acceleration due to sound source S along platform axis x_p. It is applied to digital computer 1014. The output of the low frequency loop on lead 930' is an analog representation of acceleration due to gravitational acceleration along the platform axis x_p due to the tilt of platform 1006. It can be digitized by a simple conventional analog to digital converter or the amplifier could be replaced with the binary sampler to form a low frequency Σ-Δ loop.

Similarly, accelerometer 1012 produces a serial binary bit stream on lead 168" representative of the acceleration due to sound source S along platform axis y_p. The output of the low frequency loop on lead 930" is an analog representation of acceleration due to gravitational acceleration along platform axis y_p due to the tilt of platform 1006. The analog signals are applied respectively to A/D converters 1014 and 1016 to produce digital representations of g_{xp} and g_{yp}, the measured gravitational accelerations along the x and y platform axes.

Digital computer 1018 is programmed to determine the tilt angles θ_x and θ_y from the known magnitude of the gravitational acceleration of the accelerometer in an untilted platform. After determination of such angles θ_x and θ_y, the accelerations a_{xp} and a_{yp} are converted to untilted accelerations along x and y axes of the platform. Of course, ancillary measurements of the angular orientation of the x and y axes of the platform are necessary due to the floating buoy and suspended platform. Such orientation may be determined by mounting a compass on such platform. With such compass information, accelerations determined as above along untilted x and y axes of the platform 1006 may be translated to provide an acceleration vector in the direction of sound source S.

The alternative accelerometer embodiment of Figure 24 is similar to Figure 23, but applies constant voltage V₂, -V₂ across top and bottom force support plates 920'. The serial binary bit stream on lead 168 is applied via lead 128' to charge generator 130' which applies a corresponding serial bit stream of charge to mass force plates 920 via leads 94. The analog signal is provided in a manner identical to that of Figure 23. The embodiment of Figure 24 may be used as accelerometers 1010 and 1012 as discussed above.

It is apparent that the embodiments of Figures 23 and 24 may be modified to use a.c. modulation in a

manner described in Figures 18 and 19 as discussed above.

Various modifications and alternatives in the described structures will be apparent to those skilled in the art. For example, although the preferred method of fabricating the force transducer is by chemical etching of a semi-conductor wafer, plasma etching may also be used effectively. Although the preferred N⁻ doping of the spring bases and other regions is arsenic, boron or phosphorous may also be used depending upon the original crystal type. Although the preferred method of sensing the displacement of the mass of the mass-spring-support system is by electric field means, a displacement signal representative of the position of the mass between the top and bottom support plates may be generated by piezoresistors or piezoelectric elements disposed on or in the springs which change their resistance or output voltage depending on the flex of the springs. A current through such piezoresistors would produce a voltage signal used in the same way as the voltage signal of the sense conducting plates as described above with the preferred embodiments of the invention. For this reason, these changes are desired to be included in the appended claims.

Claims

1. A transducer comprising,
 - sensing means for generating a displacement signal (122) of a mass (36, 36') from a reference position with respect to a support structure (38),
 - first forward circuit means including high pass filter means (124') responsive to said displacement signal (122) for creating a high-pass filtered displacement signal (126) and converting same to an output binary bit stream (168) representative of said high-pass filtered displacement signal,
 - second forward circuit means including low pass filter means (924) responsive to said displacement signal (122) for creating a low pass filtered displacement signal (926), and converting same to an output low frequency signal representative of said low pass filtered displacement signal,
 - first feedback circuit means (164, 166) responsive to said output binary bit stream (168) for generating a binary force on said mass in a direction tending to restore said mass (36') to said reference position,
 - second feedback circuit means (930, 932) responsive to said output low frequency signal for generating a low frequency force on said mass (36') in a direction tending to restore said mass (36') to said reference position,

whereby said output binary bit stream (168) is representative of a characteristic of motion, preferably acceleration, of said support structure (38) at frequencies passed by said high pass filter means (124') and

said output low frequency signal is representative of the acceleration of said support structure (38) at frequencies passed by said low pass filter means (924).

2. A transducer according to Claim 1 wherein said mass (36) is supported by springs (44, 46, 48) from said support structure (38), and wherein said mass has a surface with a sense conducting area (90) and first and second force conducting areas (920, 922), and said mass (36) is free to move between corresponding opposing sense conducting areas (90') and corresponding opposing first force conducting areas (920) and corresponding opposing second force conducting areas (922') on plates (82, 84) which face said surface of said mass (36) and which are secured to said support structure (38).
3. A transducer according to Claim 2 wherein said displacement signal is generated on said sense conducting area of said mass (36) by applying a d.c. potential across said opposing sense conducting areas (90') of said plates secured to said support structure (38), said binary force on said mass is generated by applying complementary binary bit streams to said opposing first force conducting areas (920') of said plates secured to said support structure (38) and by applying a constant charge to said first force conducting area (920) of said mass, and said low frequency force on said mass is generated by applying said output low frequency signal differentially respectively to said opposing second conducting areas (922') of said plates secured to said support structure (38) and by applying a constant charge to said second force conducting area (922) of said mass (36).
4. A transducer according to Claim 2 wherein said displacement signal (122) is generated on said sense conducting area (90) of said mass (36) by applying a d.c. potential across said opposing sense conducting areas (90') of said plates secured to said support structure (38), and said binary force on said mass (36) is generated by applying a d.c. potential across said opposing first force conducting areas (920') of said plates secured to said support structure (38) and by applying a binary bit stream of charge, proportional to said output binary bit stream, to said first

manner described in Figures 18 and 19 as discussed above.

Various modifications and alternatives in the described structures will be apparent to those skilled in the art. For example, although the preferred method of fabricating the force transducer is by chemical etching of a semi-conductor wafer, plasma etching may also be used effectively. Although the preferred N⁻ doping of the spring bases and other regions is arsenic, boron or phosphorous may also be used depending upon the original crystal type. Although the preferred method of sensing the displacement of the mass of the mass-spring-support system is by electric field means, a displacement signal representative of the position of the mass between the top and bottom support plates may be generated by piezoresistors or piezoelectric elements disposed on or in the springs which change their resistance or output voltage depending on the flex of the springs. A current through such piezoresistors would produce a voltage signal used in the same way as the voltage signal of the sense conducting plates as described above with the preferred embodiments of the invention. For this reason, these changes are desired to be included in the appended claims.

Claims

1. A transducer comprising,

sensing means for generating a displacement signal (122) of a mass (36, 36') from a reference position with respect to a support structure (38),

first forward circuit means including high pass filter means (124') responsive to said displacement signal (122) for creating a high-pass filtered displacement signal (126) and converting same to an output binary bit stream (168) representative of said high-pass filtered displacement signal,

second forward circuit means including low pass filter means (924) responsive to said displacement signal (122) for creating a low pass filtered displacement signal (926), and converting same to an output low frequency signal representative of said low pass filtered displacement signal,

first feedback circuit means (164, 166) responsive to said output binary bit stream (168) for generating a binary force on said mass in a direction tending to restore said mass (36') to said reference position,

second feedback circuit means (930, 932) responsive to said output low frequency signal for generating a low frequency force on said mass (36') in a direction tending to restore said mass (36') to said reference position,

whereby said output binary bit stream (168) is representative of a characteristic of motion, preferably acceleration, of said support structure (38) at frequencies passed by said high pass filter means (124') and

said output low frequency signal is representative of the acceleration of said support structure (38) at frequencies passed by said low pass filter means (924).

2. A transducer according to Claim 1 wherein said mass (36) is supported by springs (44, 46, 48) from said support structure (38), and wherein

said mass has a surface with a sense conducting area (90) and first and second force conducting areas (920, 922), and

said mass (36) is free to move between corresponding opposing sense conducting areas (90') and corresponding opposing first force conducting areas (920) and corresponding opposing second force conducting areas (922') on plates (82, 84) which face said surface of said mass (36) and which are secured to said support structure (38).

3. A transducer according to Claim 2 wherein said displacement signal is generated on said sense conducting area of said mass (36) by applying a d.c. potential across said opposing sense conducting areas (90') of said plates secured to said support structure (38),

said binary force on said mass is generated by applying complementary binary bit streams to said opposing first force conducting areas (920') of said plates secured to said support structure (38) and by applying a constant charge to said first force conducting area (920) of said mass, and

said low frequency force on said mass is generated by applying said output low frequency signal differentially respectively to said opposing second conducting areas (922') of said plates secured to said support structure (38) and by applying a constant charge to said second force conducting area (922) of said mass (36).

4. A transducer according to Claim 2 wherein said displacement signal (122) is generated on said sense conducting area (90) of said mass (36) by applying a d.c. potential across said opposing sense conducting areas (90') of said plates secured to said support structure (38), and

said binary force on said mass (36) is generated by applying a d.c. potential across said opposing first force conducting areas (920') of said plates secured to said support structure (38) and by applying a binary bit stream of charge, proportional to said output binary bit stream, to said first



force conducting area (920) of said surface of said mass (36).

5. A system for detecting the direction of acceleration forces of sound waves in a body of water (1000) comprising,

a submerged platform (1006) supported via a cable (1008) from a floating buoy (1004), said platform (1006) characterized by an x axis and a y axis, each perpendicular to each other and perpendicular to said cable (1008), said cable (1008) defining a z axis which may be tilted from true gravitational axis of the earth by wave and current action on said buoy (1004) and said platform (1006),

a first accelerometer (1010) mounted on said platform (1006) such that its axis of sensitivity is coexistent with said x axis of said platform (1006),

a second accelerometer (1012) mounted on said platform (1006) such that its axis of sensitivity is coexistent with said y axis and of said platform (1006),

each of said first and second accelerometers (1010, 1012) having

sensing means for generating a displacement signal (122) of a mass (36) from a reference position with respect to a support structure (38),

means responsive to said displacement signal (122) and including a high pass filter (124') for generating a detection signal (126) representative of acceleration of said support structure at frequencies passed by said high pass filter (124'), and

means responsive to said displacement signal (122) and including a low pass filter (924) for generating a low frequency gravitational signal (926) representative of acceleration of said support structure (38) at frequencies passed by said low pass filter (924),

first feedback circuit means (164, 166) responsive to said detection signal (126) for generating a force on said mass (36) in a direction tending to restore said mass to said reference position,

second feedback circuit means (930, 932) responsive to said low frequency gravitational signal (926) for generating a force on said mass (36) in a direction tending to restore said mass to said reference position,

means responsive to said low frequency gravitational signal (926) generated by said first accelerometer (1010) for determining the angle of tilt θ_x of said platform with respect to said true gravitational axis of the earth with respect to the platform x axis,

means responsive to said low frequency gravitational signal (926) generated by said sec-

ond accelerometer (1012) for determining the angle of tilt θ_y of said platform with respect to said true gravitational axis of the earth with respect to the platform y axis,

means responsive to said angle of tilt θ_x and said detection signal (126) of said first accelerometer (1010) for translating said detection signal along the x axis of said platform in the absence of tilt, and

means responsive to said angle of tilt θ_y and said detection signal (126) of said second accelerometer (1012) for translating said detection signal along the y axis of said platform in the absence of tilt.

6. A system according to Claim 5 further comprising means for determining the angular orientation of said x axis and said y axis with respect to said z axis.

Patentansprüche

1. Meßwertumwandler, mit:

einer Fühlereinrichtung zur Erzeugung eines Verschiebungssignals (112) einer Masse (36, 36') von einer Bezugsposition relativ zu einer Tragkonstruktion (38);

einer ersten Vorwärtsschaltungseinrichtung mit einer Hochpaßfiltereinrichtung (124'), die auf das Verschiebungssignal (112) anspricht, um ein hochpaßgefiltertes Verschiebungssignal (126) zu erzeugen und um dieses in einen binären Ausgangsbitstrom (168) umzuwandeln, der das hochpaßgefilterte Verschiebungssignal darstellt;

einer zweiten Vorwärtsschaltungseinrichtung mit einer Tiefpaßfiltereinrichtung (924), die auf das Verschiebungssignal (112) anspricht, um ein tiefpaßgefiltertes Verschiebungssignal (926) zu erzeugen und um dieses in ein Ausgangsniederfrequenzsignal umzuwandeln, welches das tiefpaßgefilterte Verschiebungssignal darstellt;

einer ersten Rückkopplungskreiseinrichtung (164, 166), die auf den binären Ausgangsbitstrom (168) anspricht, um an der Masse eine Binärkraft in eine Richtung zu erzeugen, die dazu neigt, die Masse (36') an die Bezugsposition zurückzuführen;

einer zweiten Rückkopplungskreiseinrichtung (930, 932), die auf das Ausgangsniederfrequenzsignal anspricht, um an der Masse (36') eine Niederfrequenzkraft in eine Richtung zu erzeugen, die dazu neigt, die Masse (36') an die Bezugsposition zurückzuführen;

wobei der binäre Ausgangsbitstrom (168) eine Eigenschaft der Bewegung, vorzugsweise der Beschleunigung, der Tragkonstruktion (38)



darstellt, und zwar auf Frequenzen, die durch die Hochpaßfiltereinrichtung (124') geleitet werden; und

wobei das Ausgangsniederfrequenzsignal die Beschleunigung der Tragkonstruktion (38) auf durch die Tiefpaßfiltereinrichtung (924) geleiteten Frequenzen darstellt.

2. Meßwertumwandler nach Anspruch 1, wobei die Masse durch Federn (44, 46, 48) an der Tragkonstruktion (38) getragen wird; und wobei
 - die Masse eine Oberfläche mit einem Richtungsleitungsbereich (90) und mit ersten und zweiten Kraftleitungsbereichen (920, 922) aufweist, und wobei
 - sich die Masse (36) frei an den Platten (82, 84), die zu der Oberfläche der Masse (36) gerichtet und an der Tragkonstruktion (38) befestigt sind, zwischen entsprechenden entgegengesetzten Richtungsleitungsbereichen (90') und entsprechenden entgegengesetzten ersten Kraftleitungsbereichen (920) und entsprechenden zweiten Kraftleitungsbereichen (922') bewegen kann.
3. Meßwertumwandler nach Anspruch 2, wobei das Verschiebungssignal an dem Richtungsleitungsbereich der Masse (36) durch Anlegen einer Gleichstromspannung an den entgegengesetzten Richtungsleitungsbereichen (90') der an der Tragkonstruktion (38) befestigten Platten erzeugt wird; wobei
 - die Binärkraft an der Masse durch die Zufuhr komplementärer binärer Bitströme an entgegengesetzte erste Kraftleitungsbereiche (920') der an der Tragkonstruktion befestigten Platten erzeugt wird, sowie durch Anlegen einer konstanten Ladung an den ersten Kraftleitungsbereich (920) der Masse; und wobei
 - die Niederfrequenzkraft an der Masse dadurch erzeugt wird, daß das Ausgangsniederfrequenzsignal entsprechend differential den entgegengesetzten zweiten Leitungsbereichen (922') der an der Tragkonstruktion (38) angebrachten Platten zugeführt wird, sowie durch Anlegen einer konstanten Ladung an den zweiten Kraftleitungsbereich (922) der Masse (36).
4. Meßwertumwandler nach Anspruch 2, wobei das Verschiebungssignal (112) an dem Richtungsleitungsbereich (90) der Masse (36) durch Anlegen einer Gleichstromspannung an den entgegengesetzten Richtungsleitungsbereichen (90') der an der Tragkonstruktion (38) befestigten Platten erzeugt wird; und wobei
 - die Binärkraft an der Masse (36) durch Anlegen einer Gleichstromspannung an den entgegengesetzten ersten Kraftleitungsbereichen (920') der an der Tragkonstruktion (38) befestigten

ten Platten erzeugt wird, sowie durch Zufuhr eines binären Ladungsbitstroms, der proportional zu dem binären Ausgangsbitstrom ist, an den ersten Kraftleitungsbereich (920) der Oberfläche der Masse (36).

5. System zur Erkennung der Richtung von Beschleunigungskräften von Schallwellen in einer Wassermasse (1000), mit:
 - einer Unterwasserplattform (1006), die über ein Kabel (1008) an einer Boje (1004) hängt, wobei die Plattform (1006) durch eine X-Achse und eine Y-Achse gekennzeichnet ist, die jeweils senkrecht zueinander und senkrecht zu dem Kabel (1008) angeordnet sind, wobei das Kabel (1008) eine Z-Achse bildet, die zu der echten Gravitationsachse der Erde durch Wellen- und Stromwirkung an der Boje (1004) und der Plattform (1006) schräg stehen kann;
 - einem ersten Beschleunigungsmesser (1010), der an der Plattform (1006) angebracht ist, so daß dessen Empfindlichkeitsachse auf der X-Achse der Plattform (1006) liegt;
 - einem zweiten Beschleunigungsmesser (1012), der an der Plattform (1006) angebracht ist, so daß dessen Empfindlichkeitsachse auf der Y-Achse der Plattform (1006) liegt;
 - wobei der erste und der zweite Beschleunigungsmesser (1010, 1012) jeweils folgendes umfassen:
 - eine Fühlereinrichtung zur Erzeugung eines Verschiebungssignals (112) einer Masse (36) von einer Bezugsposition relativ zu einer Tragkonstruktion (38);
 - eine Einrichtung, die auf das Verschiebungssignal (112) anspricht und die einen Hochpaßfilter (124') zur Erzeugung eines Erfassungssignals (126) aufweist, das die Beschleunigung der Tragkonstruktion auf durch den Hochpaßfilter (124') geleiteten Frequenzen darstellt; und
 - eine Einrichtung, die auf das Verschiebungssignal (112) anspricht und die einen Tiefpaßfilter (924) zur Erzeugung eines Niederfrequenzgravitationssignals (926) aufweist, das die Beschleunigung der Tragkonstruktion (38) auf durch den Tiefpaßfilter (924) geleiteten Frequenzen darstellt;
 - eine erste Rückkopplungskreiseinrichtung (164, 166), die auf das Erfassungssignal (126) anspricht, um an der Masse (36) eine Kraft in eine Richtung zu erzeugen, die dazu neigt, die Masse an die Bezugsposition zurückzuführen;
 - eine zweite Rückkopplungskreiseinrichtung (930, 932), die auf das Niederfrequenzgravitationssignal (926) anspricht, um an der Masse (36) eine Kraft in eine Richtung zu erzeugen, die dazu neigt, die Masse an die Bezugsposition zurückzuführen;



eine Einrichtung, die auf das durch den ersten Beschleunigungsmesser (1010) erzeugte Niederfrequenzgravitationssignal (926) anspricht, um den Neigungswinkel θ_x der Plattform im Verhältnis zu der echten Gravitationsachse der Erde in bezug auf die X-Achse der Plattform zu bestimmen;

eine Einrichtung, die auf das durch den zweiten Beschleunigungsmesser (1012) erzeugte Niederfrequenzgravitationssignal (926) anspricht, um den Neigungswinkel θ_y der Plattform im Verhältnis zu der echten Gravitationsachse der Erde in bezug auf die Y-Achse der Plattform zu bestimmen;

eine Einrichtung, die auf den Neigungswinkel θ_x und das Erfassungssignal (126) des ersten Beschleunigungsmessers (1010) anspricht, um das Erfassungssignal auf der X-Achse der Plattform ohne Schräge zu übersetzen; und

eine Einrichtung, die auf den Neigungswinkel θ_y und das Erfassungssignal (126) des zweiten Beschleunigungsmessers (1012) anspricht, um das Erfassungssignal auf der Y-Achse der Plattform ohne Schräge zu übersetzen.

6. System nach Anspruch 5, ferner umfassend eine Einrichtung zur Bestimmung der Winkelausrichtung der X-Achse und der Y-Achse in bezug auf die Z-Achse.

Revendications

1. Un transducteur comprenant:

- des moyens de détection pour engendrer un signal de déplacement (112) d'une masse (36, 36') depuis une position de référence définie par rapport à une structure de support (38),
- des premiers circuits en ligne directe, incluant un filtre passe-haut (124'), sensibles audit signal de déplacement (112) pour produire un signal de déplacement filtré en passe-haut (126) et pour convertir ce signal en une suite de bits binaires de sortie (168), représentative dudit signal de déplacement filtré en passe-haut;
- des seconds circuits en ligne directe, incluant un filtre passe-bas (924), sensibles audit signal de déplacement (112) pour produire un signal de déplacement filtré en passe-bas (926) et pour convertir ce signal en un signal de sortie à basse fréquence représentatif dudit signal de déplacement filtré en passe-bas;
- des premiers circuits (164-166) de contre-réaction, recevant ladite suite de bits binaires de sortie (168), pour engendrer une force

ce binaire sur ladite masse (36') dans une direction tendant à la ramener dans sa position de référence;

- des seconds circuits (930-932) de contre-réaction, recevant ledit signal de sortie à basse fréquence, pour engendrer une force à basse fréquence sur ladite masse (36') dans une direction tendant à la ramener dans sa position de référence;
- de sorte que ladite suite de bits binaires de sortie (168) est représentative d'une caractéristique de mouvement, notamment de l'accélération, de ladite structure de support (38) aux fréquences passées par ledit filtre passe-haut (124');
- et ledit signal à basse fréquence est représentatif de l'accélération de ladite structure de support (38) aux fréquences passées par ledit filtre passe-bas (924).

2. Un transducteur selon la revendication 1, dans lequel:

- ladite masse (36) est supportée par des ressorts (44, 46, 48) rattachés à ladite structure de support (38);
- ladite masse possède une surface pourvue d'une aire conductrice de détection (90) ainsi que d'une première et d'une seconde aire conductrice de force (920, 922);
- ladite masse (36) est libre de se mouvoir entre des aires conductrices de détection correspondantes opposées (90'), des premières aires conductrices de force correspondantes opposées (920) et des secondes aires conductrices de force correspondantes opposées (922'), placées sur des plaques (82, 84) disposées en regard de la surface de ladite masse (36) et fixées à ladite structure de support (38).

3. Un transducteur selon la revendication 2, dans lequel:

- ledit signal de déplacement est engendré sur ladite aire conductrice de détection de la masse (36), en appliquant une tension continue entre les aires conductrices de détection opposées (90') desdites plaques fixées à ladite structure de support (38);
- ladite force binaire exercée sur ladite masse est engendrée en appliquant des suites de bits binaires complémentaires sur les premières aires conductrices de force opposées (920') desdites plaques fixées à ladite structure de support (38), et en appliquant une charge constante sur ladite première aire conductrice de force (920) de ladite masse;
- ladite force à basse fréquence exercée sur



ladite masse est engendrée en appliquant d'une manière différentielle ledit signal de sortie à basse fréquence respectivement auxdites secondes aires conductrices de force opposées (922') desdites plaques fixées à ladite structure de support (38), et en appliquant une charge constante à ladite seconde aire conductrice de force (922) de ladite masse (36).

4. Un transducteur selon la revendication 2 dans lequel:

- ledit signal de déplacement (112) est engendré sur ladite aire conductrice de détection (90) de ladite masse (36) en appliquant une tension continue entre lesdites aires conductrices de détection opposées (90') desdites plaques fixées à ladite structure de support (38);
- ladite force binaire exercée sur ladite masse (36) est engendrée en appliquant une tension continue entre lesdites premières aires conductrices de force opposées (920') desdites plaques fixées à ladite structure de support (38), et en appliquant à ladite première aire conductrice de force (920) de la surface de ladite masse (36), une suite de bits binaires de charge, proportionnelle à ladite suite de bits binaires de sortie.

5. Un système pour détecter la direction des forces d'accélération des ondes acoustiques dans une masse d'eau (1000) comprenant:

- une plate-forme immergée (1006) soutenue par un câble (1008) solidaire d'une bouée flottante (1004), ladite plate-forme (1006) étant caractérisée par deux axes X et Y, à la fois perpendiculaires l'un à l'autre et audit câble (1008), ledit câble définissant un axe Z qui peut être incliné par rapport à l'axe de gravité réel de la terre du fait de l'action des vagues et des courants sur ladite bouée (1004) et ladite plate-forme (1006);
- un premier accéléromètre (1010) monté sur ladite plate-forme (1006) de façon que son axe de sensibilité coïncide avec l'axe X de ladite plate-forme (1006);
- un second accéléromètre (1012) monté sur ladite plate-forme (1006) de façon que son axe de sensibilité coïncide avec l'axe Y de ladite plate-forme (1006);
- chacun desdits premier et second accéléromètres (1010, 1012) possédant:
- des moyens de détection pour engendrer un signal de déplacement (112) d'une masse (36) depuis une position de référence définie par rapport à une structure de support

(38);

- des moyens, recevant ledit signal de déplacement (112) et incluant un filtre passe-haut (124'), pour engendrer un signal de détection (126) représentatif de l'accélération de ladite structure de support (38) aux fréquences passées par ledit filtre passe-haut (124');
- des moyens, recevant ledit signal de déplacement (112) et incluant un filtre passe-bas (924), pour engendrer un signal gravitationnel à basse fréquence (926), représentatif de l'accélération de ladite structure de support (38) aux fréquences passées par ledit filtre passe-bas (924);
- des premiers circuits de contre-réaction (164, 166), recevant ledit signal de détection (126) pour engendrer une force sur ladite masse (36), dans une direction tendant à ramener ladite masse à sa position de référence;
- des seconds circuits de contre-réaction (930, 932), recevant ledit signal gravitationnel à basse fréquence (926), pour engendrer une force sur ladite masse (36), dans une direction tendant à ramener ladite masse à sa position de référence;
- des moyens recevant ledit signal gravitationnel à basse fréquence (926) engendré par ledit premier accéléromètre (1010) pour déterminer l'angle d'inclinaison θ_x de ladite plate-forme par rapport à l'axe de gravité réel de la terre rapporté à l'axe X de la plate-forme;
- des moyens recevant ledit signal gravitationnel à basse fréquence (926) engendré par le second accéléromètre (1012) pour déterminer l'angle d'inclinaison θ_y de ladite plate-forme par rapport à l'axe de gravité réel de la terre rapporté à l'axe Y de la plate-forme;
- des moyens sensibles audit angle d'inclinaison θ_x et audit signal de détection (126) dudit premier accéléromètre (1010) pour translater ledit signal de détection le long de l'axe X de ladite plate-forme en l'absence d'inclinaison;
- des moyens sensibles audit angle d'inclinaison θ_y et audit signal de détection (126) dudit second accéléromètre (1012) pour translater ledit signal de détection le long de l'axe Y de ladite plate-forme en l'absence d'inclinaison.

6. Un système selon la revendication 5 comprenant en outre des moyens pour déterminer l'orientation angulaire dudit axe X et dudit axe Y par rapport audit axe Z.

