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Particle motion sensor for marine seismic sensor streamers

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(71) Applicant(s)  
PGS Americas, Inc.

(72) Inventor(s)  
Stenzel, Andre, Tenghamn, Stig Rune Lennart

(74) Agent/Attorney  
Davies Collison Cave, 1 Nicholson Street, Melbourne, VIC, 3000

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### **Abstract**

A seismic sensor is disclosed which includes at least one particle motion sensor, and a sensor jacket adapted to be moved through a body of water. The particle motion sensor is suspended within the sensor jacket by at least one biasing device. In one embodiment, a mass of the sensor and a force rate of the biasing device are selected such that a resonant frequency of the sensor within the sensor jacket is within a predetermine range.

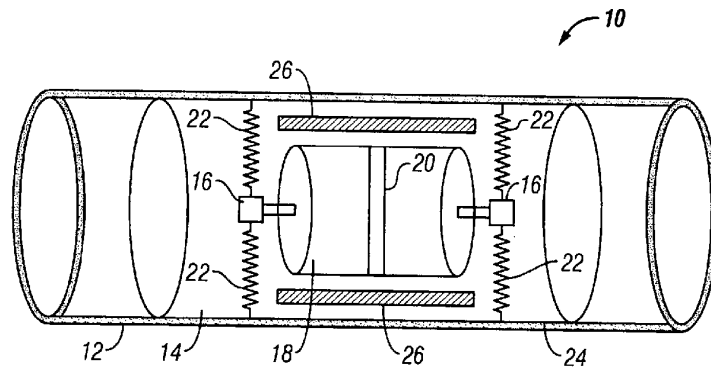


FIG. 1

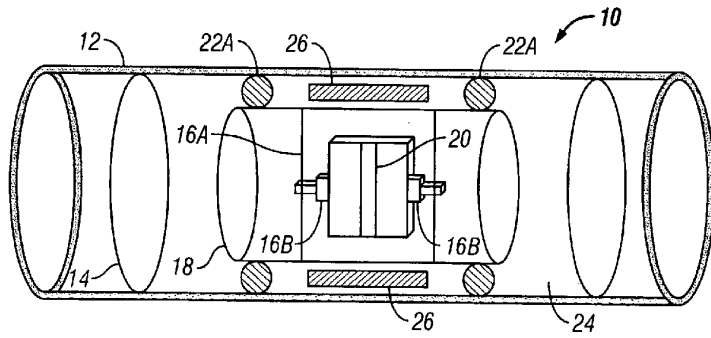


FIG. 2

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COMPLETE SPECIFICATION

NAME OF APPLICANT(S)::

**PGS Americas, Inc.**

ADDRESS FOR SERVICE:

**DAVIES COLLISON CAVE**  
Patent Attorneys  
1 Nicholson Street, Melbourne, 3000, Australia

INVENTION TITLE:

Particle motion sensor for marine seismic sensor streamers

The following statement is a full description of this invention, including the best method of performing it known to me/us:-

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### **Cross-reference to related applications**

Not applicable.

### **Statement regarding federally sponsored research or development**

Not applicable.

### **Background of the Invention**

#### **Field of the Invention**

- [0001] The invention relates generally to the field of seismic surveying systems and techniques. More specifically, the invention relates to arrangements for particle motion sensors used with marine seismic streamers.

#### **Background Art**

- [0002] In seismic exploration, seismic data are acquired by imparting acoustic energy into the earth near its surface, and detecting acoustic energy that is reflected from boundaries between different layers of subsurface earth formations. Acoustic energy is reflected when there is a difference in acoustic impedance between layers disposed on opposite sides of a boundary. Signals representing the detected acoustic energy are interpreted to infer structures of and composition of the subsurface earth structures.
- [0003] In marine seismic exploration, (seismic exploration conducted in a body of water) a seismic energy source, such as an air gun, or air gun array, is typically used to impart the acoustic energy into the earth. The air gun or air gun array is actuated at a selected depth in the water, typically while the air gun or air gun array is towed by a seismic survey vessel. The same or a different seismic survey vessel also tows one or more seismic sensor cables, called "streamers", in the water. Generally the streamer extends behind the vessel along the direction in which the streamer is towed. Typically, a streamer includes a plurality of pressure sensors, usually hydrophones, disposed on the cable at spaced apart, known positions along the cable. Hydrophones

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are sensors that generate an optical or electrical signal corresponding to the pressure of the water or the time gradient ( $dp/dt$ ) of the pressure in the water. The vessel that tows the one or more streamers typically includes recording equipment to make a record, indexed with respect to time, of the signals generated by the hydrophones in response to the detected acoustic energy. The record of signals is processed, as previously explained, to infer structures of and compositions of the earth formations below the locations at which the seismic survey is performed.

[0004] Marine seismic data often include ghosting and water layer multiple reflections, because water has a substantially different acoustic impedance than the air above the water surface, and because water typically has a substantially different acoustic impedance than the earth formations below the bottom of the water (or sea floor). Ghosting and water layer multiples can be understood as follows. When the air gun or air gun array is actuated, acoustic energy radiates generally downwardly where it passes through the sea floor and into the subsurface earth formations. Some of the acoustic energy is reflected at subsurface acoustic impedance boundaries between layers of the earth formations, as previously explained. Reflected acoustic energy travels generally upwardly, and is ultimately detected by the seismic sensors on one or more streamers. After the reflected energy reaches the streamers, however, it continues to travel upwardly until it reaches the water surface. The water surface has nearly complete reflectivity (a reflection coefficient about equal to -1) with respect to the upwardly traveling acoustic energy. Therefore, nearly all the upwardly traveling acoustic energy will reflect from the water surface, and travel downwardly once again, where it may be detected by the sensors in the streamer. The water-surface reflected acoustic energy will also be shifted in phase by about 180 degrees from the upwardly traveling incident acoustic energy. The surface-reflected, downwardly traveling acoustic energy is commonly known as a "ghost" signal. The ghost signal causes a distinct "notch", or attenuation of the energy within a particular frequency range.

[0005] The downwardly traveling acoustic energy reflected from the water surface, as well as acoustic energy emanating directly from the seismic energy source, may reflect from the water bottom and travel upwardly, where it can be detected by the sensors in the streamer. This same upwardly traveling acoustic energy will also reflect from the water surface, once again traveling downwardly. Acoustic energy

may thus reflect from both the water surface and water bottom a number of times before it is attenuated, resulting in so-called water layer reverberations. Such reverberations can have substantial amplitude within the total detected acoustic energy, masking the acoustic energy that is reflected from subsurface layer boundaries, and thus making it more difficult to infer subsurface structures and compositions from seismic data.

[0006] So-called "dual sensor" cables are known in the art for detecting acoustic (seismic) signals for certain types of marine seismic surveys. One such cable is known as an "ocean bottom cable" (OBC) and includes a plurality of hydrophones located at spaced apart positions along the cable, and a plurality of geophones on the cable, each substantially collocated with one of the hydrophones. The geophones are responsive to the velocity of motion of the medium to which the geophones are coupled. Typically, for OBCs the medium to which the geophones are coupled is the water bottom or sea floor. Using signals acquired using dual sensor cables enables particularly useful forms of seismic data processing. Such forms of seismic data processing generally make use of the fact that the ghost signal is substantially opposite in phase to the acoustic energy traveling upwardly. The opposite phase of the ghost reflection manifests itself by having opposite sign or polarity in the ghost signal as compared with upwardly traveling acoustic energy in the signals measured by the hydrophones, while the geophone signals are substantially the same polarity because of the phase reversal at the water surface and the reversal of the direction of propagation of the seismic energy. While OBCs provide seismic data that is readily used to infer subsurface structure and composition of the Earth, as their name implies, OBCs are deployed on the water bottom. Seismic surveying over a relatively large subsurface area thus requires repeated deployment, retrieval and redeployment of OBCs.

[0007] One type of streamer, including both pressure responsive sensors and particle motion responsive sensors is disclosed in U.S. Patent Application No. 10/233,266, filed on August 30, 2002, entitled, "Apparatus and Method for Multicomponent Marine Geophysical Data Gathering", and assigned to the assignee of the present invention, incorporated herein by reference. A technique for attenuating the effects of ghosting and water layer multiple reflections in signals detected in a dual sensor streamer is disclosed in U.S. Patent Application No. 10/621,222, filed on July 16,

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2003, entitled, "Method for Seismic Exploration Utilising Motion Sensor and Pressure Sensor Data," assigned to the assignee of the present invention and incorporated herein by reference.

5 [0008] Particle motion sensors in a streamer respond not only to seismic energy induced motion of the water, but to motion of the streamer cable itself induced by sources other than seismic energy propagating through the water. Motion of the streamer cable may include mechanically induced noise along the streamer cable, among other sources. Such cable motion unrelated to seismic energy may result in noise in the output of the particle motion sensors which may make interpretation of the seismic signals difficult. It is desirable, therefore, to provide 10 a streamer cable having motion sensors that reduces cable noise coupled into the motion sensors, while substantially maintaining sensitivity of the particle motion sensors to seismic energy.

15 **Summary of the Invention**

[0009] According to the present invention there is provided a seismic sensor, comprising:  
at least one particle motion sensor; and  
a sensor jacket adapted to be moved through a body of water, the particle 20 motion sensor suspended within the sensor jacket by at least one biasing device;  
a mass of the at least one particle motion sensor and a force rate of the biasing device are selected such that a resonant frequency of the sensor within the sensor jacket is within a predetermined range; and  
wherein the at least one particle motion sensor is rigidly coupled to an 25 interior of a sensor housing, the sensor housing rotatably mounted within the sensor mount, the sensor housing coupled through the at least one biasing device to the sensor jacket.

[0010] In one embodiment, a mass of the sensor and a force rate of the biasing device are selected such that a resonant frequency of the sensor within the sensor 30 jacket is within a selected frequency range.

[0010A] The invention also provides a marine seismic sensor system, comprising:



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a sensor jacket adapted to be towed by a seismic vessel moved through a body of water;

5 a plurality of particle motion sensors suspended within the sensor jacket at a selected location along the jacket, the plurality of particle motion sensors suspended in the jacket by at least one biasing device, a mass of the plurality of particle motion sensors and a force rate of the at least one biasing device selected such that a resonant frequency of the plurality of particle motion sensors within the sensor jacket is within a predetermined range; and

10 at least one pressure sensor disposed at a selected position along the sensor jacket.

[0010B] In one embodiment, a mass of each particle motion sensor and a force rate of each biasing device are selected such that a resonant frequency of each sensor within the sensor jacket is within a selected frequency range. The system may include at least one pressure sensor disposed at a selected position along the jacket.

15 [0010C] The invention also provides a marine seismic data acquisition system, comprising:

20 a marine seismic vessel adapted to a plurality of seismic sensor streamers; a plurality of seismic sensor streamers operatively coupled at one end to the vessels, each streamer comprising a jacket and a plurality of particle motion sensors suspended within the sensor jacket at each one of a plurality of selected locations along the jacket, each of the particle motion sensors suspended in the jacket by at least one biasing device; and

a plurality of pressure sensors disposed at spaced apart locations along each of the streamers.

25 [0011] Other aspects and advantages of the invention will be apparent from the following description and the appended claims.

### Brief Description of the Drawings

- [0012] Figure 1 shows a cut away view of one embodiment of a particle motion sensor in a seismic streamer according to the invention.
- [0013] Figure 2 shows a cut away view of an alternative embodiment of a particle motion sensor in a seismic streamer.
- [0014] Figure 3A shows a cut away view of another embodiment of a particle motion sensor in a marine seismic streamer having multiple motion sensors.
- [0015] Figure 3B shows a cut away view of an alternative arrangement to that shown in Figure 3A of multiple particle motion sensors.
- [0016] Figure 4 shows an example marine seismic surveying system including sensors according to the invention.

### Detailed Description

- [0017] One embodiment of a seismic sensor disposed in a section of a marine seismic sensor streamer is shown in a cut away view in Figure 1. The streamer 10 includes an exterior jacket 12 made of any material known in the art for enclosing components of a seismic sensor streamer. In the present embodiment, the jacket 12 may be formed from polyurethane. The jacket 12 in the present embodiment may include an integral strength member (not shown separately in Figure 1 for clarity). Alternatively, the streamer 10 may include one or more separate strength members (not shown) for transmitting axial load along the streamer 10. At least one sensor housing 14 is disposed inside the jacket 12 at a selected position along the jacket. Typical embodiments will include a plurality of such sensor housings disposed at spaced apart locations along the jacket 12. The sensor housing 14 may be formed from material such as plastic (including but not limited to the type sold under the trademark LEXAN<sup>®</sup>, a registered trademark of General Electric Co., Fairfield, Connecticut), steel or other high strength material known to those of ordinary skill in the art. The sensor housing 14 contains active components of a seismic particle motion sensor as will be explained below. The sensor housing 14 preferably includes slots 26 or other form of acoustically transparent window to enable particle motion within the water (not shown in Figure 1) in which the streamer 10 is suspended during operation to

pass through the wall of the sensor housing 14 where such particle motion can be detected by a particle motion sensor 20. The particle motion sensor 20 in the present embodiment is rigidly mounted inside a fluid tight enclosure 18 which may be formed from plastic, steel or other suitable material known in the art. The enclosure 18 excludes fluid from contact with transducer components of the sensor 20. Motion of the enclosure 18 is directly coupled to the particle motion sensor 20 for transduction of the particle motion into a signal such as an electrical or optical signal, as is also known in the art. The motion sensor 20 may be a geophone, an accelerometer or other sensor known in the art that is responsive to motion imparted to the sensor 20. The motion sensor 20 in the present embodiment can be a geophone, and generates an electrical signal related to the velocity of the motion sensor 20.

[0018] In the present embodiment, the jacket 12 and the sensor housing 14 are preferably filled with a liquid 24 having a density such that the assembled streamer 10 is approximately neutrally buoyant in the water (not shown in Figure 1). The liquid used to fill the jacket 12 may be the same as, or different from, the liquid used to fill the sensor housing 14. The effective density of the sensor 20 inside the enclosure 18 is also preferably such that the combined sensor 20 and enclosure 18 are approximately neutrally buoyant in the liquid 24. The viscosity of the liquid 24 is preferably such that movement of the enclosure 18 with respect to the sensor housing 14 (such movement enabled by resiliently suspending the enclosure 18 within the housing 14 as further explained below) is dampened. In the present embodiment, the liquid 24 can be synthetic oil.

[0019] The streamer 10 may rotate during seismic surveying operations, as is known in the art. It is desirable to avoid transmitting streamer rotation to the particle motion sensor 20. To decouple rotation of the streamer 10 from the particle motion sensor 20, in the embodiment of Figure 1, the enclosure 18 can be rotatably mounted inside the sensor housing 14. Rotational mounting in this embodiment includes swivels 16 disposed on opposite sides of the enclosure 18, which rotatably suspend the enclosure 18 inside the sensor housing 14 by means of biasing devices 22. In the embodiment of Figure 1, the swivels 16 may include a rotatable electrical contact of any type known in the art, such that an electrical connection is maintained across the swivel 16 irrespective of rotary orientation of the enclosure 18 inside the housing 14.

- [0020] The enclosure 18 is preferably weighted (or has a mass distribution) so as to maintain a selected rotary orientation with respect to Earth's gravity. To reduce transmission of streamer 10 rotation to the sensor 20, the liquid 24 viscosity, in addition to being selected to dampen other types of motion of the enclosure 18 within the sensor housing 14, should also be selected such that the enclosure 18 can substantially avoid being rotated when the streamer 10, and correspondingly the housing 14, are rotated. In the present embodiment, the liquid 24 viscosity is preferably within a range of about 50 to 3000 centistokes.
- [0021] The configuration shown in Figure 1, which includes the housing 14 to enclose the sensor enclosure 18 and sensor 20 therein may provide mechanical advantages over configurations which do not have a separate sensor housing 14. Such possible advantages include better resistance to damage to the sensor 20 during handling and use of the streamer 10. The principle of operation of a sensor system according to the invention, as will be further explained below, however, does not require a separate housing to enclose the motion sensor. Other embodiments may be made without having a separate sensor housing 14 inside the jacket 12, in which case, the biasing device 22 is connected, directly or indirectly to the jacket 12.
- [0022] In the present embodiment, the acoustic impedance of the jacket 12, the housing 14 and the enclosure 18 can be substantially the same as that of the water (not shown in Figure 1) surrounding the streamer 10. Having the acoustic impedance of the jacket 12, housing 14 and enclosure 18 substantially match the surrounding water improves the response of the motion sensor to seismic energy propagating through the water. Preferably, the seismic sensor (including the housing 14 and enclosure 18) has an acoustic impedance within a range of about 750,000 to 3,000,000 Newton seconds per cubic meter ( $Ns/m^3$ ).
- [0023] As previously explained, the sensor 20 is rigidly coupled to the interior of the enclosure 18. The enclosure 18 is suspended inside the housing 14, as previously described, by biasing devices 22. In the present embodiment, the biasing devices 22 can be springs. The purpose of the biasing devices 22 is to maintain position of the enclosure 18 within the housing 14, and to resiliently couple motion of the housing 14 to the enclosure 18. Because the enclosure 18 is substantially neutrally buoyant inside the housing 14, the springs 22 in the present embodiment do not need to provide a

large restoring force to suspend the enclosure 18 at a selected position inside the housing 14.

- [0024] Preferably, the springs 22 should be selected to have a force rate small enough such that the resonant frequency of the enclosure 18 suspended in the housing 14 is within a selected range. The selected range is preferably less than about 20 Hz, more preferably less than about 10 Hz. Movement of the streamer 10 above the resonant frequency will be decoupled from the enclosure 18 (and thus from the sensor 20). As is known in the art, the resonant frequency will depend on the mass of the sensor 20 and enclosure 18, and on the force rate (known as "spring rate", meaning the amount of restoring force with respect to deflection distance) of the biasing device 22. Seismic signals propagating from the subsurface through the water will be transmitted to the sensor 20, however, noise above the resonant frequency transmitted along the jacket 12 will be substantially decoupled from the sensor 20.
- [0025] In other embodiments, other forms of biasing device may be used instead of the springs 22 shown in Figure 1. For example, elastomer rings (as will be explained below with respect to Figures 2, 3A and 3B and 3) or the like may be used to suspend the enclosure 18 within the housing 14. As is the case with the springs 22 shown in Figure 1, the force rate of such elastomer rings or other biasing device should be such that a resonant frequency of the enclosure 18 within the housing 14 is within a selected range. In some embodiments, the range is less than about 20 Hz, and more preferably, is less than about 10 Hz. While springs and elastomer rings are specifically disclosed herein, it should be clearly understood that any device which provides a restoring force related to an amount of movement of the sensor (or enclosure thereof) from a neutral or rest position may be used as a biasing device. Other examples of biasing device include pistons disposed in cylinders, having a compressible fluid therein such that movement of the pistons to compress the fluid will result in a force tending to urge the pistons back to a rest position.
- [0026] In the present embodiment, the sensor 20 is oriented within the enclosure 18 such that when the enclosure 18 maintains the previously described substantially constant rotary orientation, the orientation of the sensor 20 is substantially vertical. "Sensor orientation" as used in this description means the direction of principal sensitivity of the sensor 20. As is known in the art, many types of motion sensors are responsive to motion along one selected direction and are substantially insensitive to

motion along any other direction. Maintaining the orientation of the sensor 20 substantially vertical reduces the need for devices to maintain rotational alignment of the streamer 10 along its length, and reduces changes in sensitivity of the sensor 20 resulting from momentary twisting of the streamer 10 during surveying. One purpose for maintaining substantially vertical orientation of the sensor 20 is so that the sensor 20 response will be primarily related to the vertical component of motion of the water (not shown in Figure 1) in which the streamer 10 is deployed. The vertical component of motion of the water may be used, as explained in U.S. Patent Application No. 10/621,222 previously disclosed herein, to determine upgoing components of a seismic wavefield. Other embodiments, such as will be explained below with reference to Figures 3A and 3B, include a plurality of motion sensors having sensitive axes oriented along different directions.

[0027] Another embodiment of a particle motion sensor according to the invention is shown in cut away view in Figure 2. In the embodiment shown in Figure 2, the jacket 12 can be substantially the same configuration as in the previous embodiment. The sensor housing 14 in the present embodiment may also be the same as in the previous embodiment. The interior of the jacket 12 and the interior of the housing 14 in the present embodiment are also preferably filled with liquid 24 having viscosity in a range of about 50 to 3000 centistokes as in the previous embodiment. Synthetic oil may be used for the liquid as in the previous embodiment.

[0028] The motion sensor 20 in the embodiment of Figure 2 may be an accelerometer, geophone, or any other type of motion sensor known in the art, as in the embodiment illustrated in Figure 1. As shown in Figure 2, however, the sensor 20 can be mounted on gimbal bearings 16B, including electrical swivels therein. The gimbal bearings 16B are mounted inside a gimbal frame 16A. The gimbal frame 16A is rigidly coupled to a sensor enclosure 18. The sensor enclosure 18 can be similar in exterior configuration to the sensor enclosure (18 in Figure 1) in the previous embodiment. Preferably, the gimbal bearings 16B are coupled to the sensor 20 above the center of gravity of the sensor 20 so that the sensor 20 will orient itself by gravity along a selected direction. Preferably the selected direction is such that the selected direction is substantially vertical, and corresponds to the sensitive direction of the sensor 20.

[0029] In the embodiment shown in Figure 2, the sensor enclosure 18 is suspended within the sensor housing 14 using one or more biasing devices as explained above

with respect to Figure 1. In the present embodiment, the biasing devices can be elastomer or other form of resilient rings 22A. The resilient rings 22A should have a compressibility, also referred to as "durometer" measurement or reading, (and thus have an equivalent force rate) such that the resonant frequency of the sensor enclosure 18 within the sensor housing 14 is within a selected range. In one embodiment, the resonant frequency is preferably less than about 20 Hz, or more preferably less than about 10 Hz. Alternatively, the sensor enclosure 18 may be suspended within the sensor housing 14 using springs (not shown), as in the previous embodiment. Springs and elastomer rings are only two examples of biasing devices used to suspend the sensor enclosure 18 within the sensor housing 14. One advantage of using elastomer rings, or other form of resilient ring, for the biasing device 22A is that such rings when configured as shown in Figure 2 provide substantially omnidirectional restoring force, meaning that irrespective of the direction along which the sensor enclosure 18 is moved with respect to the sensor housing 14, a corresponding restoring force is exerted by the resilient ring to urge the sensor enclosure 18 back to its rest position. As a result, using resilient rings for the biasing device can simplify the construction of a seismic sensor according to the invention.

[0030] The embodiment shown in Figure 2 has a generally cylindrically shaped enclosure 18, which is suspended by the elastomer rings 22A within the jacket 12. The jacket 12 may itself be substantially cylindrical in shape. The exact shape of the enclosure 18 and jacket 12 are not important to the principle of operation of the invention. However, the construction of a seismic sensor according to the invention can be simplified using a cylindrically shaped enclosure fitted within a cylindrically shaped jacket 12, so that the enclosure 18 is suspended in the jacket 12 only by the elastomer rings 22A.

[0031] As previously explained, it is only necessary to suspend the enclosure 18 within the housing 14 such that motion of the streamer 10 is resiliently coupled (through the biasing device – the elastomer rings 22A in the present embodiment) to the sensor enclosure 18. By resiliently coupling the motion of the streamer 10 to the enclosure 18 through the elastomer rings 22A, motion related to certain types of acoustic noise transmitted along the streamer 10 will be substantially decoupled from the sensor 20. Decoupling streamer motion from the sensor 20 can improve the signal-to-noise ration of the detected signals related to particle motion of the water

(not shown in Figure 2) in which the streamer 10 is suspended during use, as will be further explained below.

[0032] The embodiments of a sensor according to the invention described with reference to Figures 1 and 2 include various implementations of a particle motion sensor rotatably suspended inside the streamer. Rotatable suspension of the motion sensor as in the previous embodiments enables maintaining the sensitive direction of the motion sensor along a selected direction. Another embodiment, which will now be explained with reference to Figure 3A, includes a plurality of motion sensors which may be suspended inside the streamer in a rotationally fixed manner. Figure 3A shows a motion sensor enclosure 19 which is suspended inside the jacket 12 using biasing devices. In the embodiment of Figure 3A, the biasing devices can be elastomer rings 22A, which may be similar to the elastomer rings as explained above with reference to Figure 2. The elastomer rings 22A should have a durometer reading such that the resonant frequency of the enclosure 19 suspended within the jacket 12 is within a selected range. In some embodiments, the resonant frequency is less than about 20 Hz, and more preferably is less than about 10 Hz. The jacket 12 may be substantially the same construction as in the previous embodiments, including an integral strength member (not shown separately). The jacket 12 is preferably filled with liquid substantially as explained above with reference to Figures 1 and 2.

[0033] The embodiment shown in Figure 3A includes three separate particle motion sensors, shown at 20X, 20Y, 20Z, each rigidly coupled to the interior of the enclosure 19. Each of the three motion sensors 20X, 20Y, 20Z is mounted within the enclosure 19 such that the sensitive axis of each motion sensor 20X, 20Y, 20Z is oriented along a different direction. It is generally convenient to orient each of the motion sensors 20X, 20Y, 20Z along mutually orthogonal directions, however other relative orientations for motion sensors are well known in the art. The arrangement of multiple motion sensors as shown in Figure 3A may eliminate the need to provide rotatable mounting of the motion sensor enclosure 19 within the streamer 12, and further, may provide the streamer with the capability of detecting particle motion along more than one direction. As in the previous embodiments, the motion sensors 20X, 20Y, 20Z in the embodiment of Figure 3A may be geophones, accelerometers or any type other particle motion sensor known in the art. Also as in the previous embodiments, explained above with reference to Figures 1 and 2, the embodiment of



Figure 3A preferably has an effective density of the enclosure 19 having the sensors 20X, 20Y, 20Z therein such that the enclosure 19 is substantially neutrally buoyant in the liquid, so as to minimize the restoring force needed to be exerted by the elastomer rings 22A.

[0034] The embodiment shown in Figure 3A includes three mutually orthogonal motion sensors mounted within a single enclosure 19. Alternatively, and as will be explained with reference to Figure 3B, individual motion sensors, shown also as 20X, 20Y and 20Z, each having a respective enclosure 19X, 19Y, 19Z may be suspended within the jacket 12 using elastomer rings 22A, having durometer reading selected such that the resonant frequency of each of the enclosures 19X, 19Y, 19Z is less than about 20 Hz, and more preferably is less than about 10 Hz. The sensors 20X, 20Y, 20Z are arranged such that the sensitive axis of each sensor is oriented along a different direction than the other two sensors. In one embodiment, the sensitive axes of the sensors 20X, 20Y, 20Z are mutually orthogonal. The jacket 12 in the embodiment of Figure 3B is preferably filled with liquid 24 substantially as explained above with reference to Figures 1 and 2.

[0035] In order to resolve the direction from which seismic energy originates using multiple, rotationally fixed sensors as shown in Figures 3A and 3B, it is desirable to have an orientation sensor (not shown) disposed proximate the particle motion sensors. The orientation sensor may include three mutually orthogonal accelerometers, measurements from which may be used to determine the direction of Earth's gravity with respect to the streamer 10. Other embodiments may include three mutually orthogonal magnetometers, or a gyroscope, to determine the orientation of the streamer with respect to an Earth magnetic or Earth geographic reference. Such orientation sensors are well known in the art.

[0036] It will be readily apparent to those skilled in the art that the multiple sensor arrangements shown in Figures 3A and 3B may also be combined with the rotatable mounting arrangement shown in Figure 1 (including, for example, electric swivel 16 in Figure 1) to provide that multiple motion sensors each remain substantially oriented along a selected direction with respect to Earth's gravity. The embodiment explained with reference to Figure 1 provides that the single motion sensor maintains a substantially vertical orientation. In an embodiment combining rotational mounting with multiple motion sensors, the multiple motion sensors may be arranged such that

their sensitive axes remain substantially mutually orthogonal, and in some embodiments one of the sensors maintains a substantially vertical orientation.

[0037] One embodiment of a marine seismic survey system that includes particle motion sensors according to the invention is shown schematically in Figure 4. The system includes a seismic survey vessel 30 adapted to tow one or more streamers 9 through a body of water 11. The survey vessel 30 typically includes a data acquisition and recording system 32 that may include navigation devices to determine the geographic position of the vessel 30 and each one of a plurality of sensor pairs 36 disposed at spaced apart locations along the one or more streamers 9. The data acquisition and recording system 32 may also include a controller for actuating a seismic energy source 34. The source 34 may be an air gun, a water gun, or array of such guns, for example. Each of the streamers 9 in the present embodiment includes a plurality of spaced apart seismic sensor pairs 36. Each sensor pair 36 includes at least one sensor responsive to pressure, shown generally at 36B, each of which may be a hydrophone. Each sensor pair 36 also includes at least one particle motion sensor 36A. The particle motion sensor may be any one of the embodiments explained above with reference to Figures 1, 2 and 3. In the particular embodiment shown in Figure 4, each of the pressure sensors 36B and each of the particle motion sensors 36A in each sensor pair 36 are substantially collocated, or located so that seismic signals detected by each of the pressure sensor 36B and motion sensor 36A represent substantially the same part of the Earth's subsurface. Other embodiments may include more than one of each of a pressure sensor and motion sensor for each sensor pair. For example, as many as eight individual pressure sensors and eight individual motions sensors may be included in each sensor pair. Still other embodiments may include one or more pressure sensors on one or more of the streamers at locations other than collocated with each particle motion sensor.

[0038] Seismic sensors and marine seismic data acquisition systems according to the invention may provide improved detection of seismically induced particle motion in a body of water, and may provide reduced sensitivity to noise induced by motion of a seismic streamer cable.

[0039] While the invention has been described with respect to a limited number of embodiments, those skilled in the art, having benefit of this disclosure, will appreciate that other embodiments can be devised which do not depart from the scope of the

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invention as disclosed herein. Accordingly, the scope of the invention is limited in scope only by the attached claims.

Throughout this specification and the claims which follow, unless the context requires otherwise, the word "comprise", and variations such as "comprises" and "comprising", will be understood to imply the inclusion of a stated integer or step or group of integers or steps but not the exclusion of any other integer or step or group of integers or steps.

The reference to any prior art in this specification is not, and should not be taken as, an acknowledgement or any form of suggestion that that prior art forms part of the common general knowledge in Australia.

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THE CLAIMS DEFINING THE INVENTION ARE AS FOLLOWS:

1. A seismic sensor, comprising:  
at least one particle motion sensor; and  
5 a sensor jacket adapted to be moved through a body of water, the particle motion sensor suspended within the sensor jacket by at least one biasing device;  
a mass of the at least one particle motion sensor and a force rate of the biasing device are selected such that a resonant frequency of the sensor within the sensor jacket is within a predetermined range; and  
10 wherein the at least one particle motion sensor is rigidly coupled to an interior of a sensor housing, the sensor housing rotatably mounted within the sensor mount, the sensor housing coupled through the at least one biasing device to the sensor jacket.
2. The seismic sensor of claim 1 wherein the sensor jacket is filled with a liquid  
15 having a density selected so that the sensor jacket is substantially neutrally buoyant when the sensor jacket is suspended in a body of water.
3. The seismic sensor of claim 2 wherein the liquid has a viscosity in a range of about  
20 50 to 3,000 centistokes.
4. The seismic sensor of claim 1 wherein the motion sensor is rotatably suspended  
within the sensor jacket and has a mass distribution such that the motion sensor maintains a selected rotary orientation.
- 25 5. The seismic sensor of claim 4 wherein the rotatable suspension comprises gimbal bearings, the gimbal bearings supported in a frame coupled through the at least one biasing device to an interior of the sensor jacket.
6. The seismic sensor of claim 4 wherein the selected orientation is substantially  
30 vertical.

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7. The seismic sensor of claim 4 wherein the rotatable mounting suspension comprises a swivel adapted to enable rotation of the at least one of the sensor and sensor housing while maintaining electrical contact through the swivel.
- 5 8. The seismic sensor of claim 2 wherein the at least one motion sensor, the sensor jacket and the liquid when combined have an acoustic impedance in a range of about 750,000 Newton-seconds per cubic meter and 3,000,000 Newton-seconds per cubic meter.
9. The seismic sensor of claim 1 wherein the resonant frequency is less than about 20  
10 Hz.
10. The seismic sensor of claim 1 wherein the resonant frequency is less than about 10 Hz.
- 15 11. The seismic sensor of claim 1 wherein at least one biasing device comprises a spring.
12. The seismic sensor of claim 1 wherein the at least one biasing device comprises an elastomer ring.
- 20 13. The seismic sensor of claim 1 wherein the sensor housing comprises at least one acoustically transparent window.
14. The seismic sensor of claim 2 wherein the sensor housing is formed from plastic  
25 having a density substantially equal to the density of the liquid.
15. The seismic sensor of claim 1 wherein the motion sensor comprises a geophone.
16. The seismic sensor of claim 1 wherein the motion sensor comprises an  
30 accelerometer.

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17. The seismic sensor of claim 1 wherein the particle motion sensor comprises three motion sensors each having a sensitive axis disposed along a different selected direction.
18. The seismic sensor of claim 17 wherein the selected directions are mutually  
5 orthogonal.
19. The seismic sensor of claim 1 wherein the jacket comprises an integral strength member.
- 10 20. A marine seismic sensor system, comprising:  
a sensor jacket adapted to be towed by a seismic vessel moved through a body of water;  
a plurality of particle motion sensors suspended within the sensor jacket at a selected location along the jacket, the plurality of particle motion sensors suspended in the  
15 jacket by at least one biasing device, a mass of the plurality of particle motion sensors and a force rate of the at least one biasing device selected such that a resonant frequency of the plurality of particle motion sensors within the sensor jacket is within a predetermined range; and  
at least one pressure sensor disposed at a selected position along the sensor jacket.
- 20 21. The seismic sensor system of claim 20 wherein the sensor jacket is filled with a liquid having a density selected such that the sensor jacket is substantially neutrally buoyant when the sensor jacket is suspended in a body of water.
- 25 22. The seismic sensor system of claim 21 wherein the liquid has a viscosity in a range of about 500 to 1,000 centistokes.
23. The seismic sensor system of claim 20 wherein each motion sensor is rotatably suspended within the sensor jacket and has a mass distribution such that each motion  
30 sensor maintains a selected rotary orientation.

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24. The seismic sensor system of claim 23 wherein each rotatable suspension comprises gimbal bearings, the gimbal bearings supported in a frame coupled through the at least one biasing device to an interior of the sensor jacket.
- 5 25. The seismic sensor system of claim 23 wherein the selected orientation of at least one of the plurality of motion sensors is substantially vertical.
26. The seismic sensor system of claim 23 wherein each rotatable mounting suspension comprises a swivel adapted to enable full rotation of each motion sensor while maintaining  
10 electrical contact through the swivel.
27. The seismic sensor system of claim 21 wherein each motion sensor, the sensor jacket and the liquid when combined have an acoustic impedance in a range of about 750,000 Newton-seconds per cubic meter and 3,000,000 Newton-seconds per cubic meter.  
15
28. The seismic sensor system of claim 20 wherein the resonant frequency is less than about 20 Hz.
29. The seismic sensor system of claim 20 wherein the resonant frequency is less than  
20 about 10 Hz.
30. The seismic sensor system of claim 20 wherein the at least one biasing device comprises a spring.
- 25 31. The seismic sensor system of claim 20 wherein the at least one biasing device comprises a resilient ring.
32. The seismic sensor system of claim 20 wherein each motion sensor comprises a geophone.  
30

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33. The seismic sensor system of claim 20 wherein each motion sensor comprises an accelerometer.

34. The seismic sensor system of claim 20 wherein the plurality of motion sensors  
5 comprises three motion sensors each having a sensitive axis disposed along a different selected direction.

35. The seismic sensor system of claim 34 wherein the different selected directions are mutually orthogonal.

10

36. The seismic sensor system of claim 20 wherein the jacket comprises an integral strength member.

37. The seismic sensor system of claim 20 further comprising a plurality of pressure  
15 sensors disposed along the jacket at locations substantially collocated with the motion sensors.

38. The seismic sensor system of claim 20 wherein the at least one pressure sensor comprises a hydrophone.

20

39. A marine seismic data acquisition system, comprising:  
a marine seismic vessel adapted to a plurality of seismic sensor streamers;  
a plurality of seismic sensor streamers operatively coupled at one end to the  
vessels, each streamer comprising a jacket and a plurality of particle motion sensors  
25 suspended within the sensor jacket at each one of a plurality of selected locations along the jacket, each of the particle motion sensors suspended in the jacket by at least one biasing device; and

a plurality of pressure sensors disposed at spaced apart locations along each of the streamers.

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40. The seismic system of claim 39 wherein each jacket is filled with a liquid having a density selected such that each jacket is substantially neutrally buoyant when each sensor jacket is suspended in a body of water.
- 5 41. The seismic system of claim 39 wherein each of the motion sensors is rotatably suspended within one of the plurality of jackets with respect to its centre of gravity such that each motion sensor maintains a selected rotary orientation.
42. The seismic system of claim 39 wherein each rotatable suspension comprise gimbal  
10 bearings, the gimbal bearings supported in a frame coupled through the at least one biasing device to an interior of the sensor jacket.
43. The seismic system of claim 40 wherein the selected orientation of at least one of the motion sensors in each jacket is substantially vertical.
- 15 44. The seismic system of claim 40 wherein each rotatable mounting suspension comprises a swivel adapted to enable full rotation of the rotatably suspended sensor while maintaining electrical contact through the swivel.
- 20 45. The seismic system of claim 41 wherein each rotatable suspension is filled with a liquid having a viscosity in a range of about 500 to 1,000 centistokes.
46. The seismic system of claim 40 wherein each motion sensor, each jacket and the liquid when combined have an acoustic impedance in a range of about 750,000 Newton-  
25 seconds per cubic meter and 3,000,000 Newton-seconds per cubic meter.
47. The seismic system of claim 39 wherein a mass of each particle motion sensor and a force rate of each biasing device selected such that a resonant frequency of each particle motion sensor within the sensor jacket is within a predetermined range.
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48. The seismic system of claim 47 wherein the resonant frequency is less than about 20 Hz.
49. The seismic sensor system of claim 47 wherein the resonant frequency is less than  
5 about 10 Hz.
50. The seismic system of claim 39 wherein each biasing device comprises a spring.
51. The seismic system of claim 39 wherein each biasing device comprises an  
10 elastomer ring.
52. The seismic system of claim 39 wherein selected groups of the motion sensors are rigidly coupled to an interior of a sensor housing, each sensor housing rotatably mounted within one of the plurality of jackets.  
15
53. The seismic system of claim 52 wherein each sensor housing is filled with a liquid such that the effective density of the housing substantially equal to the density of the liquid which fills the jacket.
- 20 54. The seismic system of claim 52 wherein each sensor housing comprises at least one acoustically transparent window.
55. The seismic system of claim 39 wherein each motion sensor comprises a geophone.
- 25 56. The seismic system of claim 39 wherein each motion sensor comprises an accelerometer.
57. The seismic system of claim 39 wherein selected groups of the motion sensors comprise three motion sensors each having a sensitive axis disposed along a different  
30 selected direction.

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58. The seismic system of claim 57 wherein the selected directions are mutually orthogonal.

59. The seismic system of claim 39 wherein each jacket comprises an integral strength  
5 member.

60. The seismic system of claim 39 further comprising a plurality of pressure sensors disposed along each jacket, each pressure sensor disposed at a location substantially collocated with each of the motion sensors.

10

61. The seismic system of claim 60 wherein the pressure sensors comprise hydrophones.

62. A seismic sensor; a marine seismic sensor system; or a marine seismic data  
15 acquisition system substantially as hereinbefore described with reference to the accompanying drawings.

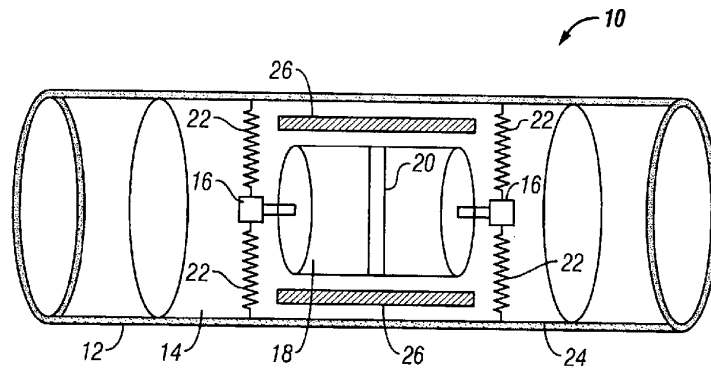


FIG. 1

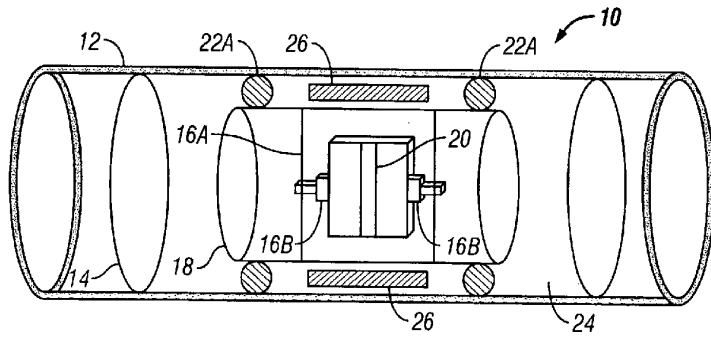


FIG. 2

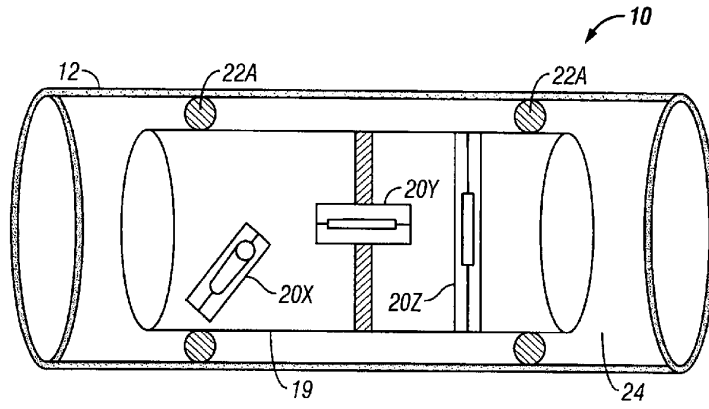


FIG. 3A

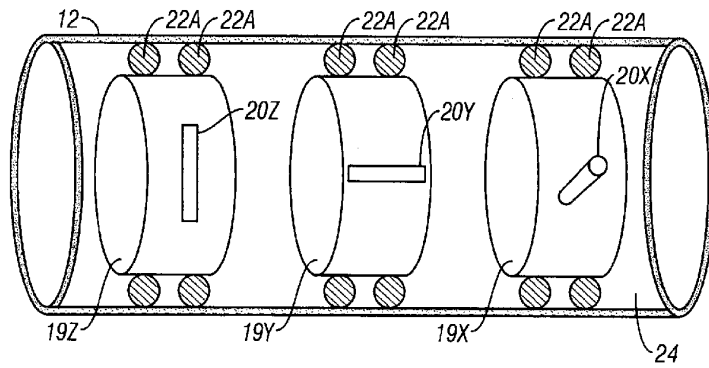


FIG. 3B

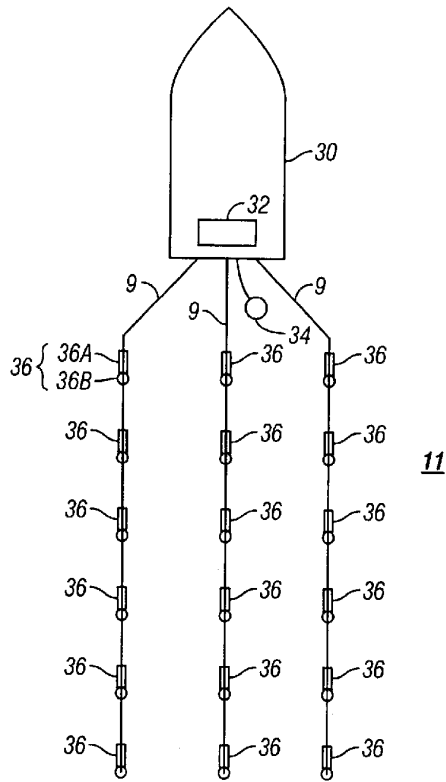


FIG. 4