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(71) Applicant (for all designated States except US): **TECHNOLOGICAL RESOURCES PTY LTD** [AU/AU]; 120 Collins Street, Melbourne, Victoria 3000 (AU).

(72) Inventor; and

(75) Inventor/Applicant (for US only): **VAN KANN, Frank, Joachim** [AU/AU]; 42 Loftus Street, Nedlands, Western Australia 6009 (AU).

(74) Agent: **GRIFFITH HACK**; Level 19, 109 St Georges Terrace, Perth, Western Australia 6000 (AU).

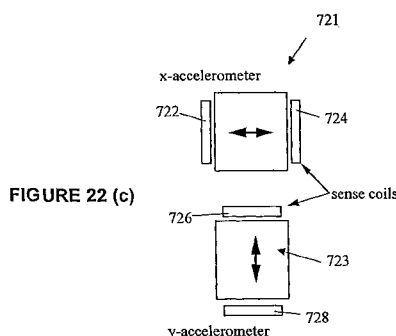
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(54) Title: A DETECTOR FOR DETECTING A GRAVITY GRADIENT



(57) Abstract: The present disclosure provides a gravity gradiometer for detecting a gravity gradient. The gravity gradiometer comprises at least two sensor masses that are pivotable about respective axes and each experience a change in torque in response to a change in gravity gradient whereby the at least two sensor masses move relative to each other in response to the change in gravity gradient and wherein a signal indicative of the gravity gradient is generated in response to the relative movement of the at least two sensor masses. Further, the gravity gradiometer comprises an acceleration sensor for sensing an acceleration associated with an external acceleration applied to the gravity gradiometer. The gravity gradiometer also comprises an actuator for generating an adjustment force that is dependent on an acceleration sensed by the acceleration sensor. The adjustment force is also dependent on a mechanical response parameter associated with at least one of the at least two sensor masses. The adjustment force is applied such that a difference between the magnitudes of the torques experienced by the at least two sensor masses in response to the change in gravity gradient is reduced.

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A DETECTOR FOR DETECTING A GRAVITY GRADIENTField of the Invention

The present invention relates to a detector for detecting
5 a gravity gradient and a gravity gradiometer.

Background of the Invention

Gravimeters are used in geological exploration to measure
the first derivatives of the earth's gravitational field.
10 Whilst some advances have been made in developing
gravimeters which can measure the first derivatives of the
earth's gravitational field, because of the difficulty in
distinguishing spatial variations of the field from
temporal fluctuations of accelerations of a moving
15 vehicle, these measurements can usually be made to
sufficient precision for useful exploration only with
land-based stationary instruments.

Gravity gradiometers (as distinct from gravimeters) are
20 used to measure the second derivative of the gravitational
field and use a sensor which is required to measure the
differences between gravitational forces down to one part
in 10^{12} of normal gravity.

25 A gravity gradiometer typically has a sensor in the form
of at least one sensor mass that experiences a change in
torque in response to a change in gravity gradient.

Gravity gradiometers have been used to attempt to locate
30 deposits such as ore deposits including iron ore and
geological structures bearing hydrocarbons. It would be
convenient if gravity gradiometers could be positioned in
aircrafts for such analyses. However, aircraft

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accelerations result in torques that are much larger than those associated with the gravity gradient. A reduction of an influence of such aircraft accelerations on the sensor provides a technological challenge.

5

Summary of the Invention

The present invention provides in a first aspect A gravity gradiometer for detecting a gravity gradient, comprising:

10 at least two sensor masses that are pivotable about respective axes and each experience a change in torque in response to a change in gravity gradient whereby the at least two sensor masses move relative to each other in response to the change in gravity gradient and wherein a
15 signal indicative of the gravity gradient is generated in response to the relative movement of the at least two sensor masses;

 an acceleration sensor for sensing an acceleration associated with an external acceleration applied to the
20 gravity gradiometer; and

 an actuator for generating an adjustment force that is dependent on an acceleration sensed by the acceleration sensor, the adjustment force being also dependent on a mechanical response parameter associated with at least one
25 of the at least two sensor masses and the adjustment force being applied such that a difference between the magnitudes of the torques experienced by the at least two sensor masses in response to the change in gravity gradient is reduced.

30

The mechanical response parameter may be dependent on a mechanical responsiveness of the at least one sensor mass to an applied force. In one embodiment the mechanical

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response parameter is dependent on a magnitude of a mass dipole moment of the at least one sensor mass of the at least two sensor masses.

- 5 The actuator and the acceleration sensor may form a part of a feed-forward control arrangement for controlling the adjustment force.

In one example the acceleration sensor is arranged to
10 sense a linear acceleration.

The pivot may be a flexure web.

The mechanical response parameter associated with at least
15 one of the at least two sensor masses may dependent on a distance between a centre of mass and the respective axis of rotation of the at least one sensor mass. The centre of mass of each sensor mass may be located in the proximity of the respective axes and at least a portion of the
20 difference between the torques experienced by the sensor masses may be a consequence of different locations of the centres of mass relative to the respective axis.

The respective axes may be aligned so as to be coaxial.
25

Each sensor mass may have a centre of mass that is displaced from the respective axis of rotation by a distance that is less than 1 part in 10^6 , less than one part in 5×10^6 or even less than one part in 10^7 of a of a
30 radius of gyration of the sensor mass.

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The centre of mass of each sensor mass is located within 5nm of the respective axis.

5 The at least two sensor masses may be pivotable within one plane and the gravity gradiometer may be arranged so that a difference between the torques experienced by the at least two sensor masses in response to the change in gravity gradient is reduced for an acceleration applied in any direction within the plane.

10

At least a portion of the acceleration sensor may be located at a fixed location relative to one of the at least two sensor masses.

15 The gravity gradiometer may comprise capacitors that are arranged such that the relative movement of the at least two sensor masses generates an electrical signal in the capacitors.

20 Alternatively, the gravity gradiometer may comprise inductive coils that are arranged such that the relative movement of the at least two sensor masses generates an electrical signal in the inductive coils. The at least two sensor masses may be positioned in a Dewar and the gravity
25 gradiometer may comprise superconducting components that in use operate at cryogenic temperatures.

The gravity gradiometer may comprise a stabilisation platform and the acceleration sensor may be located on a
30 payload side of the stabilisation platform

The present invention provides in a second aspect a method of detecting a gravity gradient signal using a detector

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comprising at least two sensor masses that are movable and each experience a change in torque in response to a change in gravity gradient whereby the at least two sensor masses move relative to each other;

5 determining an response parameter associated with at least one of the at least two sensor masses;

 sensing an acceleration associated with an external acceleration;

 generating an adjustment force that is applied such
10 that a difference between the magnitudes of the torques experienced by the at least two sensor mass is reduced, the adjustment force being dependent on a sensed acceleration and a determined response parameter; and

 detecting the gravity gradient signal.

15

The external acceleration may be a linear acceleration and the response parameter may dependent on a mass dipole moment of the at least one sensor mass.

20 The invention will be more fully understood from the following description of specific embodiments of the invention. The description is provided with reference to the accompanying drawings.

25

Brief Description of the Drawings

Figure 1 is a schematic view of a gravity gradiometer according to a specific embodiment of the present invention.

30 Figure 2 is a perspective view of a first mount forming part of a mounting of the gravity gradiometer of according to the specific embodiment of the present invention;

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Figure 3 is a perspective view of a second mount of the mounting according to a specific embodiment of the present invention;

Figure 4 is a perspective view from underneath the mount shown in Figure 3;

Figure 5 is a view of the assembled structure;

Figure 6 is a perspective view showing assembled components of the gravity gradiometer according to another specific embodiment of the present invention;

Figure 7 is a plan view of a sensor mass according to a specific embodiment of the present invention;

Figure 8 is a diagram showing actuator control according to a specific embodiment of the present invention;

Figure 9 is a perspective view of components of a gravity gradiometer according to a specific embodiment of the present invention;

Figure 10 is a perspective view of a first mount of a mounting according to another specific embodiment of the present invention;

Figure 11 is a perspective view of part of the mounting of Figure 10 to illustrate the location and extent of the flexural web of the first mount;

Figure 12 is a perspective view of the mounting of Figure 10 from beneath;

Figure 13 is a perspective view of the mounting of Figure 10 including a second mount of the second embodiment;

Figure 14 is a perspective view of a second mount component;

Figure 15 is a perspective view of the second mount component of Figure 14 from above;

Figure 16 is a perspective view of assembled

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components of the gravity gradiometer according to a specific embodiment of the present invention;

Figure 17 is a plan view of a housing portion for supporting a sensor mass according to a further embodiment
5 of the invention;

Figure 18 shows a component of the gravity gradiometer according to an embodiment of the present invention;

Figure 19 (a) - (f) is a view of transducer elements
10 according to a specific embodiment of the present invention;

Figure 20 is a view similar to Figure 18 but showing one of the transducers elements of Figure 19 in place;

Figure 21 is a diagram to assist explanation of the
15 circuits of Figures 22;

Figure 22 (a) - (d) are circuit diagram relating to a specific embodiments of the invention;

Figure 23 is a frequency tuning circuit according to an embodiment of the present invention;

20 Figures 24 to 26 show circuitry according to embodiments of the present invention;

Figure 27 is a cross-sectional perspective view through an actuator according to a specific embodiment of the invention;

25 Figure 28 (a) and (b) shows components of the gravity gradiometer according to a specific embodiment of the present invention; and

Figures 29 and 30 show block diagrams illustrating the operation of a rotatable support system according to a
30 specific embodiment of the present invention.

Detailed Description of the Specific Embodiments

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Figure 1 is a schematic view of a gravity gradiometer 1 according to a specific embodiment of the present invention. The gravity gradiometer 1 is arranged for vertical positioning relative to a ground plane.

5 Throughout this specification the ground plane coincides with an x-y plane of an x,y,z-coordination system and the gravity gradiometer is in this embodiment arranged for rotation about the z-axis and oriented in a manner such that the Γ_{xy} and $(\Gamma_{xx}-\Gamma_{yy})$ components of the gravity
10 gradient tensor can be measured.

The function of the gravity gradiometer 1 may be briefly summarised as follows. The gravity gradiometer has in this embodiment two substantially identical sensor masses which
15 are pivotally mounted on a mounting so that they can oscillate relative to the mounting. The sensor masses with mounting are rotated about the z-axis and with an angular frequency that approximately equals half the resonance frequency of sensor masses. A gravity gradient will result
20 in a force on the sensor masses which will then oscillate relative to the mounting during that rotation. Components of the gravity gradient tensor can be determined from the oscillating movement of the sensor masses relative to each other. For further details on the general principal of
25 such measurements are described in the applicants co-pending PCT international patent application number PCT/AU2006/001269.

The gravity gradiometer shown in Figure 1 comprises a
30 housing 2 which is connected to an external support structure 3 ("external platform"), which is positioned on a suspension comprising springs and dampers arranged to reduce an impact of an external liner acceleration having

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a frequency above a few Hz, such as 3, 5 or 10 Hz. The external platform 3 is arranged for rotation of the housing 2 at a suitable angular frequency about the z-axis. Further, the external platform 3 is arranged for
5 adjusting an orientation of the housing 2 about three orthogonal axes. An internal support structure ("internal platform") comprises the sensor masses and is positioned within the housing 2. The internal platform is arranged for fine adjustment of the rotation about the z-axis in a
10 manner such that transmission of an external angular acceleration about the z-axis to the sensor masses is further. The resultant z-axis rotation, as experienced by the sensor masses, is of high precision and any remaining angular accelerations about or along the x- and y-axes are
15 reduced electronically by processing a signal indicative of the gravity gradiometer generated by the gravity gradiometer 1.

The following will describe components and function of the
20 gravity gradiometer 1 in detail.

With reference to Figure 2, a first mount 10 is now described. The first mount 10 forms a part of rotatable mounting 5 which is shown in Figure 5. The mount 10
25 comprises a base 12 and an upstanding peripheral wall 14. The peripheral wall 14 has a plurality of cut-outs 16. The base 12 supports a hub 18.

Figures 3 and 4 show a second mount 20 which comprises a
30 peripheral wall 22 and a top wall 24. The peripheral wall 22 has four lugs 13 for supporting the mounting 5 in the housing 2. The top wall 24 and the peripheral wall 22 define an opening 28. The second mount 20 is mounted on

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the first mount 10 by locating the hub 18 into the opening 28 and the lugs 13 through respective cut-outs 16 as is shown in Figure 5.

5 The first mount 10 is joined to the second mount 20. The flexure web 31 is formed in the first mount 10 so that a primary mount portion of the mount 10 can pivot about a flexure web 31 relative to a secondary mount portion of the mount 10. This will be described in more detail with
10 reference to the second embodiment shown in Figures 10 to 16.

The mounting 5 mounts the sensor 40 (which will be described in more detail hereinafter and which is
15 typically in the form of a mass quadruple) for fine rotational adjustment about the z-axis for stabilising the gradiometer during the taking of measurements particularly when the gradiometer is airborne. As described above, rotational stabilisation about the x-and y-axis is in this
20 embodiment provided by the external platform only. The gravity gradiometer 1 is arranged so that in use the mounting 5 is oriented parallel to the x-y plane.

Figure 6 shows sensor 40 mounted on the mounting. The
25 sensor 40 is an Orthogonal Quadruple Responder - OQR sensor formed of a first sensor mass and a second sensor mass in the form of a first sensor mass 41 and a second sensor mass 42 (not shown in Figure 6) orthogonal to the sensor mass 41 and which is of the same shape as the
30 sensor mass 41.

The sensor mass 41 is positioned in a first housing portion 45 and the sensor mass 42 is positioned in a

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second housing portion 47. The sensor mass 41 and the second housing portion 45 is the same as the sensor 42 and the second housing portion 47 except that one is rotated 90° with respect to the other so that the sensor masses 41 and 42 are orthogonal. Hence only the first housing portion 45 will be described.

The first housing portion 45 has an end wall 51 and a peripheral side wall 52a. The end wall 51 is connected to rim 75 (Figures 2 and 5) of the wall 14 of the first mount 10 by screws or the like (not shown). The sensor mass 41 is formed by a cut 57 in the wall 51 except for a second flexure web 59 which joins the sensor mass 41 to the wall 51. The second flexure web 59 is shown enlarged in the top view of the sensor mass 41 in Figure 7. Thus, the sensor mass 41 is able to pivot in the x-y plane relative to the first housing portion 45 in response to changes in the gravitational field. The sensor mass 42 is mounted in the same way as mentioned above and also can pivot in the x-y plane relative to the second housing portion 47 in response to changes in the gravitational field about a third flexure web. The second housing portion 47 is connected to base 12 (Figure 2) of the first mount 10.

The sensor mass 41 and the first housing portion 45 together with the second flexure web 59 are an integral monolithic structure.

Transducers 71 (not shown in Figures 2 to 4) are provided for measuring the movement of the sensor masses 41 and 42 and for producing output signals indicative of the relative movement in the x-y plane and therefore of the gravity gradient.

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Figure 8 is a schematic block diagram showing actuator control to stabilise the gradiometer by rotating the mounting 5 about the z-axis. A controller 50 which may be a computer, microprocessor or the like outputs signals to actuators 53 and 54, which are arranged to rotate the mounting 5 about the z-axis. Each actuator is positioned stationary relative to lugs 13 and coupled to the first mount 10 so that the actuator can effect a rotation by a small angle of the mount 10 with other components relative to the lugs 13 (and other components that are stationary relative to the lugs 13). Each actuator provides a linear movement and is positioned so that the linear movement is translated into a small rotation of the mount 10. The actuators will be described in more detail with reference to Figure 27. The position of the mounting 5 is monitored so that appropriate feedback can be provided to the controller 50 and the appropriate control signals provided to the actuators to rotate the support 10 about the z-axis as is required to stabilise the support during movement through the air either within or towed behind an aircraft.

The specific embodiment also includes angular accelerometers which are similar in shape to the sensor masses 41 and 42 but the shape is adjusted for zero quadruple moment. The linear accelerometers are simple pendulous devices with a single micro pivot acting as the flexural hinge.

Figure 9 is a cut away view of components of the gravity gradiometer ready for mounting in the housing 1 which in turn is to be mounted in the external platform 2.

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The transducers 71 measure the angle of displacement of the sensor masses 41 and 42 and control circuitry (not shown) is configured to measure the difference between them.

5

In this embodiment, the transducers 71 are constant charge capacitors, which will be described in more detail with reference to Figure 22.

10 Figures 10 to 15 show a second embodiment in which like parts indicate like components to those previously described.

In the second embodiment the first mount 10 has cut-outs
15 80 which effectively form slots for receiving lugs (not shown) which are connected to the mount 10 in the cut-outs 80 and also to the second mount 20 shown in Figures 15 and 16. In this embodiment the lugs are separate components so that they can be made smaller, and more easily, made
20 than being cut with the second mount section 20.

In Figure 10 a cut 87 is made to define the part 18a of the hub 18. The cut 87 then extends radially inwardly at 88 and then around central section 18c as shown by cut
25 101. The cut 101 then enters into the central section 18c along cut lines 18d and 18e to define a core 18f. The core 18f is connected to the central section 18c by the flexural web 31 which is an uncut part between the cut lines 18e and 18d. The part 10a therefore forms a primary
30 mount portion of the mount 10 which is separated from a secondary mount portion 10a of the mount 10 except for where the portion 18a joins the portion 10a by the flexural web 31. The part 18a effectively forms an axle

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to allow for rotation of the part 18a relative to the part 10a in the z direction about the flexure web 31.

As is shown in Figure 11, the cut line 88 tapers outwardly from the upper end shown in Figure 11 to the lower end and the core 18c tapers outwardly in corresponding shape.

As is apparent from Figures 10, 12 and 13, the first mount 10 is octagonal in shape rather than round, as in the previous embodiment.

Figure 14 shows a component of the second mount 20 for mounting in the first mount 10. As is best shown in Figures 14 and 15, the second mount 20 has cut-outs 120 which register with the cut-outs 80 for receiving lugs (not shown). The lugs can bolt to the second mount 20 by bolts which pass through the lugs and into bolt holes 121. The lugs (not shown) are mounted to the mount 20 before the mount 20 is secured to the first mount 10.

20

In this embodiment, top wall 24 is provided with a central hole 137 and two attachment holes 138a. Three smaller holes 139a are provided to facilitate pushing of the first housing portion 45 off the part 18a if disassembly is required. When the second mount 20 is located within the first mount 10, the upper part of central section 18c projects through the hole 137, as best shown in Figure 13. The mount 20 can then be connected to the mount 10 by fasteners which pass through the holes 138 and engage in holes 139b (see Figure 10) in the part 18a.

Thus, when the first housing portion 45 and its associated sensor mass 41 is connected to the rim 75 of the first

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mount 10 and the second housing portion 47 is connected to the base 12, flexure web 31 allows movement of the housing portions 45 and 47 about the z-axis.

5 Consequently, when the second mount 20 is fixed to the part 18a, the second mount 20 can pivot with the first portion 10a of the first mount 10 about a z-axis defined by the flexure web 31 whilst the second portion formed by the part 18a remains stationary.

10

Figure 16 shows main body 61 of the housing 1 and connectors 69 with the hemispherical ends removed.

Figure 17 is a plan view of the first housing portion 45 according to a still further embodiment of the invention. As is apparent from Figure 17, the first housing portion 45 is circular rather than octagonal, as is the case with the embodiment of Figure 6.

20 The first housing portion 45 supports sensor mass 41 in the same manner as described via flexure web 59 which is located at the centre of mass of the sensor mass 41. The sensor mass 41 is of chevron shape, although the chevron shape is slightly different to that in the earlier
25 embodiments and has a more rounded edge 41e opposite flexure web 59 and a trough-shaped wall section 41f, 41g and 41h adjacent the flexure web 59. The ends of the sensor mass 41 have screw-threaded bores 300 which receive screw-threaded members 301 which may be in the form of
30 plugs such as grub screws or the like. The bores 300 register with holes 302 in the peripheral wall 52a of the first housing portion 45. The holes 302 enable access to the plugs 301 by a screwdriver or other tool so that the

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plugs 301 can be screwed into and out of the bore 300 to adjust their position in the bore to balance the sensor mass 41 so the centre of gravity is at the flexure web 59.

5 As drawn in Figure 17, the bores 300 are at a 45° angle to the horizontal and vertical. Thus, the two bores (302 shown in Figure 17) are at right angles with respect to one another.

10 Figure 17 also shows openings 305 for receiving a portion of the transducers 71 for monitoring the movement of the sensor mass 41 and producing signals in response to the movement. Typically, each transducer 71 is in the form of a constant charge capacitor. One capacitor plate typically
15 is mounted to the sensor mass 41 and another capacitor plate is stationary relative to the sensor mass 41 so that a gap is defined between the capacitor plates. Movement of the sensor mass changes the gap which in turn changes a voltage across the constant charge capacitor.

20

Figure 18 is a more detailed view of part of the housing portion of Figure 17 showing the openings 305. As can be seen from Figure 18, the openings 305 have shoulders 401 which form grooves 402.

25

Figure 19 (a) to (f) show portions of the constant charge capacitor transducers 71. The transducer shown in Figure 19 (a) comprises two electrodes. A first electrode is in this embodiment provided by a surface of the sensor masses
30 41 or 42, which are at ground potential, and a second electrode is shown in Figure 19 (a) (plate 408 a).

Figure 19 (b) shows the second capacitor electrode which

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comprises two separate capacitor elements 408b and 407b which are not in electrical contact. Again, the first electrode is provided by the sensor masses 41 or 42, which are at ground potential. The capacitor element 408b
5 surrounds the capacitor element 407b. This arrangement is used for generating a "virtual capacitor", which will be described below with reference to Figure 22.

Figure 19 (c) and (d) show alternatives to the embodiment
10 shown in Figure 19 (b) and the shown second electrodes comprise adjacent elements 408c, 407c and 408d and 407d respectively.

Figures 19 (e) and (f) show capacitor elements according
15 to further embodiments of the present invention. The second electrode comprises three capacitor elements 408e, 407e, 407f and 408f, 407g and 407h, respectively, and this arrangement is also used for generating a "virtual capacitor which will be described below.

20

It will be appreciated, that in variation of this embodiment the capacitor plates may have any other suitable cross-sectional shape.

25 As an example, Figure 20 shows the location of the capacitor elements 407b and 408b in the opening 305 and opposite a corresponding second capacitor plate 411. In this embodiment the capacitor elements 407b and 408b are provided in the form of metallic foils that are positioned
30 on insulating body 409. The plate 411 is metallic and positioned on the sensor mass 41. In this embodiment plate 411 provides one capacitor element that opposes capacitor elements 407 b and 408 b. In this case the sensor mass 41

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may be of relatively low electrical conductivity or may be electrically insulating.

If the sensor mass 41 is provided in the form of a
5 metallic material of sufficiently high electrical conductivity, the sensor mass 41 may also provide a capacitor element and a portion of the sensor mass 41 may directly oppose the capacitor elements 407b and 408b without the plate 411, as discussed above in the context
10 of Figure 17.

Figure 21 is a diagram of the sensor masses 41 and 42 showing them in their "in use" configuration. The transducers which are located in the openings 305 are
15 shown by reference numbers 71a to 71e.

As will be apparent from Figure 21, four transducers 71 are arranged adjacent the ends of the sensor mass 41. The second housing portion 47 also has four transducers
20 arranged adjacent the sensor mass 42. Thus, eight transducers 71 are provided in the gradiometer.

Referring now to Figures 22 and 23 transducer circuitry 360 is now described. Each of the transducers 71a to 71e
25 is a constant charge capacitor and comprises a first capacitor electrode. Each of the transducers 71a to 71e has a second capacitor electrode that is positioned opposite a respective first capacitor electrode and fixed in position relative to the housing portions. The first
30 capacitor electrode is in this embodiment provided by a surface the sensor masses 41 or 42. For example, each transducer 71a - 71e may have a second electrode of the type as shown in Figure 19.

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Oscillating movement of the sensor masses 41 and 42 results in a movement of the first capacitor electrodes (surfaces of the sensor masses 41 or 42) relative to the second capacitor electrodes. That movement changes the gaps between respective first and second capacitor electrodes and results in a voltage change across the constant charge capacitor transducers 71a to 71e.

If the transducers are of the type as shown in Figure 19 (b) to 20 (d), then separate component transducers are formed between the first electrode and each capacitor element of the second electrode, such as 407b and 408b. In this case Figure 22 shows the transducer circuitry for the component transducers formed between the first plate and one of the two elements and an analogous circuitry (labeled accordingly) is used for the component transducers formed between the first electrode and the other capacitor elements.

If the transducers are of the type as shown in Figure 19 (e) and 19 (f), then separate component transducers are formed between the first electrode and each of the three capacitor elements, such as 408e, 408e and 407f. Figure 22 shows the transducer circuitry for the component transducers formed between the first electrode and one of the three elements and two analogous circuitries (labeled accordingly) are used for the component transducers formed between the first plate and the other capacitor elements.

Each constant charge capacitor component transducer 71a to 71e has a separate bias voltage by a respective bias voltage source $V_{B\alpha\beta\gamma}$ applied to it. Figure 22 shows

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component transducer 71a to 71e with one of the capacitor elements being connected to ground potential. As discussed above, these capacitor elements are surfaces of the sensor masses 41 and 42, which are in this embodiment

5 electrically conductive and connected to ground potential.

The polarities of the voltages provided by the bias voltage sources 361a to 361e and the electrical interconnections between the constant charge capacitor component transducers 71a to 71e are chosen so that the

10 electrical signals generated by all transducers are combined with the same polarity if the sensor masses 41 and 42 oscillate in opposite directions. Such oscillation in opposite directions typically is generated by a gravity gradient if the sensor masses are balanced and have

15 identical mechanical properties. If the sensor masses 41 and 42 move in the same direction, one half of the electrical signals generated by the constant charge capacitors component transducers 71a to 71e has one polarity and the other half has an opposite polarity.

20 Consequently, in this case, the electrical signals typically cancel each other. Such movement in the same direction may for example be generated by a sudden movement of the aircraft in which the gravity gradiometer is positioned and consequently the transducer circuitry
25 360 illustrated in Figure 22 reduces the effect of such sudden movements and the effect of a number of other external forces or external angular accelerations that are not related to the gravity gradient.

30 The combined electrical signal is directed to a low noise amplifier which will be described in the context of Figure 23.

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The transducer circuitry 360 shown in Figure 22 also comprises locking capacitors $C_{S\alpha\beta\gamma}$ which are arranged so that the applied bias voltages $V_{B\alpha\beta\gamma}$ cannot reach the lower noise amplifier. The locking capacitors 362a to 362e
5 typically have a capacitance that is larger than 10 times, or even larger than 100 times that of the respective constant charge capacitor component transducers 71a to 71e.

10 Further, the transducer circuitry 360 comprises resistors $R_{B\alpha\beta\gamma}$ 363a to 363e. These resistors typically have a very high resistance, such as $1G\Omega$ or more, and are arranged for substantially preventing flow of charges and thereby providing for the component transducers 71a to 71e to
15 operate as constant charge capacitors.

The bias voltages applied to the constant charge capacitors generate electrostatic forces. Consequently, each transducer 71a to 71e can also function as an
20 actuator.

If the transducers 71 are of the type as shown in Figure 19(a), then the circuitry 360 shown in Figure 22 is sufficient. However in a specific embodiment of the
25 present invention the transducers are of the type as shown in Figures 19 (b) to 19(d) and comprise two component transducers. In this case two circuitries 360 are used, one for the component transducers formed between the first electrodes and one of the capacitor elements, and the
30 other for the component transducers formed between the first electrodes and the other capacitor elements. This is schematically indicated in Figure 25. A first circuitry 360 is used for measurement purposes (differential mode,

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"DM") and a second circuitry 360 is used to provide feedback for external rotational motion correction (common mode, "CM"), which will be described below with reference to Figures 28 and 29.

5

Alternatively, the circuitries 360 may also be connected so that "virtual capacitors" are formed. This will be described below in more detail and is schematically indicated in Figure 24.

10

In another specific embodiment of the present invention the transducers are of the type as shown in Figures 19 (e) or 19 (f) and comprise three component transducers. In this case three circuitries 360 are used. This is schematically indicated in Figure 26. In this embodiment two circuitries 360 are used for measurement purposes and arranged so that "virtual capacitors" are formed. A third circuitry 360 is used to provide feedback for external rotational motion correction.

20

The following will describe how relative mechanical properties of the sensor masses 41 and 42 can be tuned. The resonance frequencies of the sensor masses 41 and 42 depend on the square of the electrostatic forces and therefore the square of the applied bias voltage. For example, the resonance frequencies may be tuned using a mechanical test set up in which external forces are applied to the sensor masses 41 and 42. If the resonance frequencies are not identical, the bias voltages can be adjusted until the resonance frequencies are identical.

30

The sensitivities of the transducer capacitors for sensing the movement of the sensor masses is linearly dependent on

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the electrostatic forces and thereby linearly dependent on the applied bias voltages. Consequently, it is possible to tune both the resonance frequencies and the sensitivities of the transducers.

5

As described above, the sensor masses 41 and 42 are arranged so that a movement of the sensor masses 41 and 42 relative to each other is indicative of a change in gravity gradient. An external acceleration, such as an

10 external angular acceleration about the z-axis does not result in a movement of the sensor masses relative to each other as long as the sensor masses are identical. The sensor masses 41 and 42 and their respective flexure webs are mechanically arranged so that their moment of inertia
15 are sufficiently similar, and the transducers 71 are adjusted so that their sensitivities are sufficiently similar, so that an impact of an external angular acceleration is reduced by a factor of 10^3 to 10^4 . As a consequence the sensor masses 41 and 42 are formed as
20 discussed above to have nearly identical resonance frequencies to within 1 part in 10^3 , typically within 1 part in 10^4 . An impact of an external angular acceleration is further reduced using feed-back and feed-forward arrangements. The feed-back and feed-forward like
25 arrangements, which will be described with reference to Figure 29 and 30, result in a reduction of an influence of an external angular acceleration by a factor of approximately $10^3 - 10^4$.

30 Further, the sensor masses 41 and 42 are mechanically balanced so that a distance between a centre of mass and the axis of rotation is less than one part in 10^6 , typically 1 part in 10^7 of a radius of gyration of the

- 24 -

sensor mass, which requires a high level of mechanical precision.

Each sensor mass 41 and 42 may have a small remaining
5 imbalance (may be by a distance of the order of one or
more 10^{-9} m) from the axis about which the sensor masses 41
and 42 are arranged to rotate. Such a "mass dipole
moment" imbalance, which results in a residual influence
of an external linear acceleration, is taken into account
10 in the following manner.

A feed-forward loop is formed by components including the
transducer sensors 71, an acceleration sensor ((not shown,
but similar to acceleration sensors 721 and 723 shown in
15 Figure 22(c)) such as an additional capacitance sensor,
and control electronics. The acceleration sensor is
positioned at a fixed position relative to a housing
portion 45 or 47 and, when an external linear acceleration
is sensed, provides a voltage to a controller (not shown).
20 The controller then causes the transducer sensors 71 to
generate a suitable adjustment force that is aimed to
counteract a difference in torque that the sensor masses
41 and 42 would experience as a consequence of the
external linear acceleration. For this purpose a
25 mechanical response parameter is required that is a
measure for a ratio of an external linear acceleration and
a corresponding adjustment force required to counteract a
torque resulting from the external linear acceleration.
Consequently, the mechanical response parameter is
30 dependent on the mass dipole moment of the sensor masses
41 and 42 and the spring constants of the respective
flexure webs. The mechanical response parameter is
determined experimentally by exposing the sensor masses 41

- 25 -

and 42 in their respective housings to a linear acceleration and then determining a force that is required to compensate for a difference in torque that the sensor masses 41 and 42 would otherwise experience as a
5 consequence of the external linear acceleration. As the sensor masses 41 and 42 are arranged for movement in the x, y- plane such an imbalance only needs to be considered for acceleration within that plane.

10 In the embodiment described above the transducer sensors 71 are provided in the form of capacitors that also function as actuators. It is to be appreciated that in an alternative embodiment the gravity gradiometer 1 may also comprise suitable inductive coils that replace the
15 capacitors 71 and have corresponding sensing and actuating functions. The gravity gradiometer in accordance with the alternative embodiment comprises electronic components that accommodate the function of the inductive coils as sensors and actuators. PCT international application
20 number PCT/AU2006/001269 discloses a gravity gradiometer having inductive coils for sensing a relative motion of sensor masses. The gravity gradiometer disclosed in PCT/AU2006/001269 is cooled cooling using liquid helium and the inductive coils are superconducting devices. The
25 following will describe how the gravity gradiometer disclosed in PCT/AU2006/001269 can be adapted to account for the above-described "mass dipole moment" imbalance.

The PCT international application no. PCT/AU2006/001269
30 discloses coil arrangements ("sense coils") that are used for sensing a motion of the sensor bars and coil arrangements ("spring coils") that are used for tuning mechanical properties of the sensor bars. Anyone of the

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spring coils may be replaced by a circuitry as shown in Figure 22 (b).

The superconducting circuitry 700 comprises a spring coil
5 702 that has inductance L_F and in use carries a static
persistent current i_0 which flows through a heat switch
704 and a ballast inductor 706. The heat switch 704 is
used to initially establish the current i_0 , whose
magnitude is chosen to provide frequency tuning for the
10 respective sensor mass. Because i_0 is persistent, no
current needs to flow in the pump leads (except initially
to establish i_0). The spring coil 702 is typically a thin
film and the ballast coil 706, which has an inductance
much smaller than that of the spring coil 702, is either a
15 small thin film coil on the back of the spring coil or may
simply consist of the stray inductance associated with the
heat switch 704 and its leads.

The current i_0 produces a static force. An external
20 current i that is passed into the pump leads is splits
proportionally to flow through both L_F and L_B so that the
force can be modified that is generated by the current in
through the spring coil 702.

25 Figure 22 (c) shows x-and y linear accelerometers 721 and
723, respectively. The accelerometers 721 and 723 comprise
coils 722, 724 and 726, 728, respectively and generate
currents i_x and i_y that are proportional to the linear
acceleration of sensor masses positioned between pairs of
30 the coils.

The generated currents i_x and i_y are directed to the
above-described inductive coil circuitry 700 so that a

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force is generated by the spring coil 702 that is dependent on the currents generated by the accelerometers 721 and 723. Figure 22 (d) shows a circuit diagram 720 that illustrates how currents may be injected into the
5 spring coil 702.

The following will describe further details of electronic circuitry used in the gravity gradiometer 1.

10 Figure 23 shows a schematic circuit diagram of a low noise amplifier according to a specific embodiment of the present invention. The low noise amplifier circuitry 366 is used to amplify the electrical signal generated by the transducer circuit 360 and to provide active feedback to
15 control properties of the transducers and sensor masses 41 and 42.

The amplifier circuit 366 simulates an impedance Z_L and an ohmic component of Z_L provides active damping of resonant
20 electrical signals generated by the constant charge capacitor component transducers 71a to 71e described above. The active damping reduces the Q-factor of the resonance and thereby increases the bandwidth within which the resonance can be generated. That electrical damping
25 results in mechanical damping by generating electrostatic damping forces at the constant charge capacitor component transducers 71a - 71e. Typically, the active damping is adjusted so that the gravity gradiometer has a bandwidth of the order of 1 Hz and the Q-factor of the active
30 damping is close to 0.5.

The impedance Z_L also has an imaginary component, which is dependent on a simulated capacitance C_L in parallel with

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the simulated resistor R_L . The imaginary component actively controls the resonance frequency of the sensor masses 41 and 42 via the constant charge capacitor transducers 71a - 71e by simulating a change of the "stiffness" of the pivotal coupling of the sensor masses 41 and 42 and thereby fine-tunes the resonance frequency of the sensor masses 41 and 42. As described above, the transducer circuit 360 is arranged so that resonant oscillations in which the sensor masses 41 and 42 oscillate in opposite directions result in an additive electrical signal. The simulated capacitance C_L of the simulated impedance Z_L allows fine tuning of the resonance and thereby further helps distinguishing that resonance oscillation from other common mode oscillations in which the sensor masses 41 and 42 oscillate in the same direction.

In this embodiment the amplifier circuit 366 provides "cold damping", which introduces very little thermal noise. Passive damping, such as damping using a conventional resistor, is avoided as this would result in thermal noise.

As described above, the constant charge component capacitors 71a - 71e may combine sensing and actuator functions. The amplifier circuit 366 provides an active feedback loop between sensing and actuator functions and provides electronic feedback control of mechanical properties of the sensor masses 41 and 42.

The amplifier circuit 366 comprises an input 368 and an output 369. Further, the amplifier circuit 366 comprises a low-noise j-FET differential amplifier 370 and impedances Z_1 , Z_2 and Z_3 . The low noise amplifier 370 has two input

- 29 -

terminals 371 and 372 and the impedance Z_1 is connected between the output terminal 369 and the low noise amplifier input 371. The impedance Z_2 is connected between the output terminal 369 and the low noise amplifier input
 5 372. The impedance Z_3 is connected between the terminal 372 and a common ground terminal 373.

The amplifier circuit 366 simulates the impedance Z_L with

$$Z_L \approx -\frac{Z_1 Z_3}{Z_2} \quad (\text{eq.1})$$

10

The amplifier 370 has noise matched resistance $R_{\text{opt}} = \sqrt{\frac{S_v}{S_i}}$.

The term S_v is the spectral density of amplifier's voltage noise and the term S_i is the spectral density of amplifier's current noise. In this embodiment the
 15 amplifiers noise matched resistance is a few $1\text{M}\Omega$.

Further, the amplifier 370 has a noise temperature

$$T_{\text{opt}} = \frac{\sqrt{S_v S_i}}{2k_B} \quad (k_B: \text{Bolzman constant}) \text{ of less than } 1\text{K}.$$

20 The noise density S_r of the gradient error produced by thermal noise near resonance is given by

$$S_r = \frac{4k_B T_{\text{opt}} 2\pi f_0}{m\lambda^2 Q_{\text{act}}} \quad (\text{eg. 2})$$

25

where λ is the radius of the gyration of the sensor masses 41 and 42 and Q_{act} the effective Q-factor associated with the active damping, M is the mass of the sensor masses 41 and 42 and f_0 is the resonance frequency. The noise density

- 30 -

S_r is dependent on the noise of the amplifier and not on the physical temperature of the amplifier circuit, which allows "cold damping" and control of other mechanical properties without introducing significant thermal noise
5 at normal operation temperatures such as at room temperature.

The component transducers 71a, 71b, 71g and 71h are also used to form angular accelerometers for measuring the
10 angular movement of the mounting 5 so that feedback signals can be provided to compensate for that angular movement.

Figure 27 shows an actuator for receiving the control
15 signals to adjust the mounting in response to angular movement of the mounting 5.

The actuator shown in Figures 27 is also schematically shown in Figure 8 by reference to numerals 53 and 54. The
20 actuators are the same and Figure 28 will be described with reference to the actuator 54.

The actuator 54 comprises in this embodiment a permanent NdFeB magnet 410, a soft iron core 411, a non-magnetic
25 spacer 412 (aluminium, delrin), mumetal or permalloy housing 413, a voice coil assembly 414, a hollow rod 428 and a tube 430 that forms part of the housing 413 and in which the hollow rod 428 is rotatably mounted.

30 The voice coil assembly 414 is mounted onto rod 430 and the permanent magnet 410 and the soft iron core 411 are provided with internal bores through which the rod 430 penetrates so that the rod 430 with voice coil assembly

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414 can move axially relative to the iron core 311 and the magnet 410. Electrical connections for the voice coil assembly 414 are fed through the hollow rod 430.

5 As described above, one or both of the sensor masses 41 and 42 can also be used as an angular accelerometer to provide a measure of angular movement of the mounting 5 so that appropriate feedback signals can be generated to compensation for that movement by control of the actuators
10 previously described.

Figures 28 (a) and (b) show schematic plan and cross-sectional view of the gravity gradiometer 1. As indicated previously, the gravity gradiometer 1 comprises a housing
15 2 that is rotated by an external mounting about a z-axis. The external platform 3 comprises an inner stage 500 and an intermediate stage 502 and an outer stage 504. The housing 2 is mounted so that it is rotated with the inner stage 500 by z-drive 508 with bearings. The z-drive
20 provides continuous rotation at a very stable speed. The rotational frequency is in this embodiment selectable between 0 and 20 Hz. The intermediate stage 502 including the inner stage 500 is rotatable about the x-axis by x-drive 510, which includes bearings and the outer stage 504 is
25 rotatable with the intermediate stage 502 about the y-axis by y-axis drive 512 which also include suitable bearings. The outer stage with y-axis drive is mounted on springs 516 in a support frame 518.

30 The external platform 3 includes an IMU (inertial measurement unit), which contains gyroscopes, accelerometers, GPS receivers and a computer. The IMU is not shown in Figure 28 (a) or (b). The IMU measures

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rotation about the x-, y- and z- axis and is coupled to drives in a feedback loop. This will be described below in more detail with reference to Figure 29.

- 5 The external platform is arranged to gyro-stabilize the housing 2 about the x-, y- and z-axis with a gain factor of approximately 100 DC and a bandwidth of 20 Hz. This is achieved using the above-described 3-axis "gimbal" bearing arrangement with direct drive torque motors (508, 510 and
- 10 512). In this embodiment, fine-tuning of the motor drive for correction of rotation about the z-axis is achieved using the "common mode" signal provided by respective transducer components positioned within the housing 2.
- 15 Figure 29 shows a block diagram 600 that illustrates how the common mode signal, generated within the housing 2 (which comprises the internal platform), is used for rotational z-axis correction of the external platform.
- 20 Blocks 602 and 604, labelled "response to motion" and "response to force" respectively, both represent the gimbal structure of the support structure 3. Each gimbal consists of three main components, namely a frame, a part supported by the frame via a bearing and an actuator which
- 25 applies a torque (force) to this part. Each gimbal has two independent inputs, namely motion applied to the frame and a force applied directly to the part suspended by the frame. It has only one output, namely the angular position of the supported part and this responds differently to the
- 30 two inputs.

Feedback force F_e counteracts an external disturbance Z . This may be expressed by the following equation

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$$X_e = H_f F_e + H_z Z \quad (\text{eq. 3})$$

where H_f and H_z are constants.

5

Equation 3 may be written as

$$X_e = H_f (F_e + K_e Z) \quad (\text{eq. 4})$$

10 where $K_e = H_z/H_f$.

An external motion, such as a motion of an aircraft in which the gravity gradiometer 1 is positioned, produces an equivalent force $K_e Z$, which is counteracted by F_e

15 generated by the actuator 610. In Figure 29 block 602 "Response to motion" represents K_e and block 604 "Response to force" represents H_e . The sensor 606 for the external platform is the IMU, which contains gyroscopes, accelerometers, GPS receivers and a computer. This
20 provides a signal (usually digital) which measures the angular position and angular rate of the supported part of the innermost gimbal. This signal is used in the controller 608 (also usually digital) to implement the feedback.

25 The internal platform may be represented in an analogous manner where blocks 612 and 614 labelled "response to motion" and "response to force" respectively, both represent the z-axis gimbal structure within the housing 2. The transducer sensors 71 and the actuator 54 have been
30 described above.

In the above-described embodiment the gravity gradiometer 1 is arranged so that rotation about the z-axis is

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controlled by the external platform to a fixed uniform rotation speed. The input signal for controlling the motion is provided by the IMU 609 and the sensor 606. However, the IMU 609 and the sensor 606 typically only
5 have limited accuracy at higher frequencies and to improve the z-axis rotational correction further, an angular acceleration derived from the above-described "Common Mode" signal from the internal transducer sensors 71 is used for fine-tuning. As described above, the same signal
10 is also used inside the internal platform in a feedback loop to stabilise the instrument against applied angular acceleration (via the actuator 54). The specification for this internal feedback system is stringent and to ease this requirement, some of the burden is transferred to the
15 external platform in that manner.

Figure 30 shows a block diagram 650 that illustrates stabilisation (no rotation) about the x-and y- axis, which is performed exclusively by the external platform. All
20 elements of Figure 30 were already described above and function in an analogous manner to inhibit rotation about the x- and y- axes.

Although the invention has been described with reference
25 to particular examples, it will be appreciated by those skilled in the art that the invention may be embodied in many other forms. For example, the transducers may not necessarily be provided in the form of constant charge capacitors, but may be provided in the form of any other
30 suitable type of capacitor including those that do not allow simulation of a virtual capacitor. Further, it is to be appreciated that the amplifier circuitry 366 shown in Figure 24 is only one embodiment and a variety of

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variations from the described embodiment are possible.

In a variation of the above-described embodiment the gravity gradiometer is not arranged for rotation about the z-axis and the internal platform is arranged so that fine-adjustment of the motion of the sensor masses is conducted about the x, y and z-axes. In this case the gravity gradiometer typically comprises superconducting components and the above-described transducer sensors 71 may be provided in the form of superconducting coils. Such an arrangement is described in detail in the applicant's co-pending in PCT International Application PCT/AU2006/001276.

In addition, the gravity gradiometer may be arranged for measuring other components of the gravity gradient, in which case the gravity gradiometer would not be arranged for operation in the described orientation. For example, the gravity gradiometer may be arranged to measure the Γ_{yz} and $(\Gamma_{zz}-\Gamma_{yy})$ or Γ_{xz} and $(\Gamma_{zz}-\Gamma_{yy})$ of the gravity gradient.

The reference that is being made to PCT application number PCT/AU2006/001269 and PCT application number PCT/AU2007/001276 does not constitute an admission that these documents form a part of the common general knowledge in Australia or in any other country.

In the claims which follow and in the preceding description of the invention, except where the context requires otherwise due to express language or necessary implication, the word "comprise" or variations such as "comprises" or "comprising" is used in an inclusive sense, i.e. to specify the presence of the stated features but

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not to preclude the presence or addition of further features in various embodiments of the invention.

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The Claims defining the Invention are as Follows:

1. A gravity gradiometer for detecting a gravity gradient, comprising:

5 at least two sensor masses that are pivotable about respective axes and each experience a change in torque in response to a change in gravity gradient whereby the at least two sensor masses move relative to each other in response to the change in gravity gradient and wherein a
10 signal indicative of the gravity gradient is generated in response to the relative movement of the at least two sensor masses;

an acceleration sensor for sensing an acceleration associated with an external acceleration applied to the
15 gravity gradiometer; and

an actuator for generating an adjustment force that is dependent on an acceleration sensed by the acceleration sensor, the adjustment force being also dependent on a mechanical response parameter associated with at least one
20 of the at least two sensor masses and the adjustment force being applied such that a difference between the magnitudes of the torques experienced by the at least two sensor masses in response to the change in gravity gradient is reduced.

25

2. The gravity gradiometer as claimed in claim 1 wherein the mechanical response parameter is dependent on a mechanical responsiveness of the at least one sensor mass to an applied force.

30

3. The gravity gradiometer as claimed in claim 1 wherein the mechanical response parameter is dependent on a

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magnitude of a mass dipole moment of the at least one sensor mass of the at least two sensor masses.

4. The gravity gradiometer as claimed in any one of
5 claims 1 to 3 wherein the actuator and the acceleration sensor form a part of a feed-forward control arrangement for controlling the adjustment force.

5. The gravity gradiometer as claimed in any one of the
10 preceding claims wherein the acceleration sensor is arranged to sense a linear acceleration.

6. The gravity gradiometer as claimed in any one of the preceding claims wherein the mechanical response parameter
15 associated with at least one of the at least two sensor masses is dependent on a distance between a centre of mass and the respective axis of rotation of the at least one sensor mass.

20 7. The gravity gradiometer of claim 5 or 6 wherein the pivot is a flexure web.

8. The gravity gradiometer as claimed in claim 6 or 7 wherein the centre of mass of each sensor mass is located
25 in the proximity of the respective axes and wherein at least a portion of the difference between the torques experienced by the sensor masses is a consequence of different locations of the centres of mass relative to the respective axis.

30

9. The gravity gradiometer of any one of the preceding claims wherein the respective axes are aligned so as to be coaxial.

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10. The gravity gradiometer as claimed in any one of the preceding claims wherein each sensor mass has a centre of mass that is displaced from the respective axis of
5 rotation by a distance that is less than 1 part in 10^6 of a radius of gyration of the sensor mass.

11. The gravity gradiometer as claimed in any one of the preceding claims wherein each sensor mass has a centre of
10 mass that is displaced from the respective axis of rotation by a distance that is less than 1 part in 5×10^6 of a radius of gyration of the sensor mass.

12. The gravity gradiometer as claimed in any one of the preceding claims wherein each sensor mass has a centre of
15 mass that is displaced from the respective axis of rotation by a distance that is less than 1 part in 10^7 of a radius of gyration of the sensor mass.

20 13. The gravity gradiometer as claimed in any one of the preceding claims wherein the adjustment force is applied such that a centre of mass of each sensor mass is located within 10nm of the respective axis.

25 14. The gravity gradiometer as claimed in claim any one of the preceding claims wherein a centre of mass of each sensor mass is located within 5nm of the respective axis.

15. The gravity gradiometer as claimed in any one of the preceding wherein the at least two sensor masses are
30 pivotable within one plane and wherein the gravity gradiometer is arranged so that a difference between the torques experienced by the at least two sensor masses in

- 40 -

response to the change in gravity gradient is reduced for an acceleration applied in any direction within the plane.

16. The gravity gradiometer as claimed in any one of the preceding claims wherein at least a portion of the acceleration sensor is located at a fixed location relative to one of the at least two sensor masses.

17. The gravity gradiometer of any one of the preceding claims comprising capacitors that are arranged such that the relative movement of the at least two sensor masses generates an electrical signal in the capacitors.

18. The gravity gradiometer of any one of claims 1 to 16 comprising inductive coils that are arranged such that the relative movement of the at least two sensor masses generates an electrical signal in the inductive coils.

19. The gravity gradiometer of claim 18 wherein the at least two sensor masses are positioned in a Dewar and wherein the gravity gradiometer comprises superconducting components that in use operate at cryogenic temperatures.

20. The gravity gradiometer of any one of the preceding claims comprises a stabilisation platform and wherein the acceleration sensor is located on a payload side of the stabilisation platform

21. A method of detecting a gravity gradient signal using a detector comprising at least two sensor masses that are movable and each experience a change in torque in response to a change in gravity gradient whereby the at least two sensor masses move relative to each other;

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determining a mechanical response parameter associated with at least one of the at least two sensor masses;

5 sensing an acceleration associated with an external acceleration;

generating an adjustment force that is applied such that a difference between the magnitudes of the torques experienced by the at least two sensor mass is reduced, the adjustment force being dependent on a sensed acceleration
10 and a determined mechanical response parameter; and
detecting the gravity gradient signal.

22. The method of claim 21 wherein the external acceleration is a linear acceleration.

15

23. The method of claim 21 or 22 wherein the mechanical response parameter is dependent on a mass dipole moment of the at least one sensor mass.

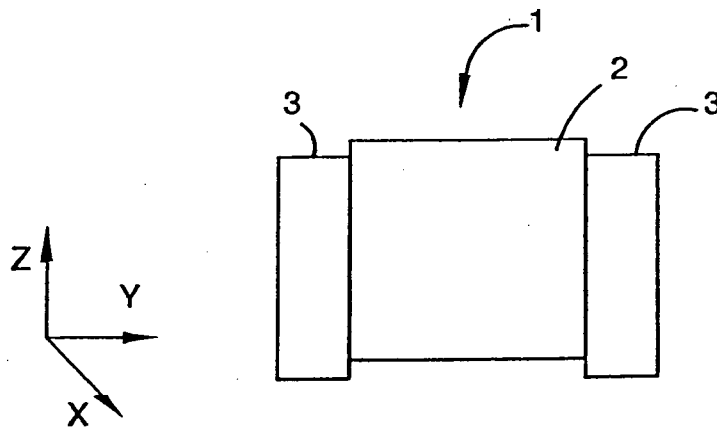


FIGURE 1

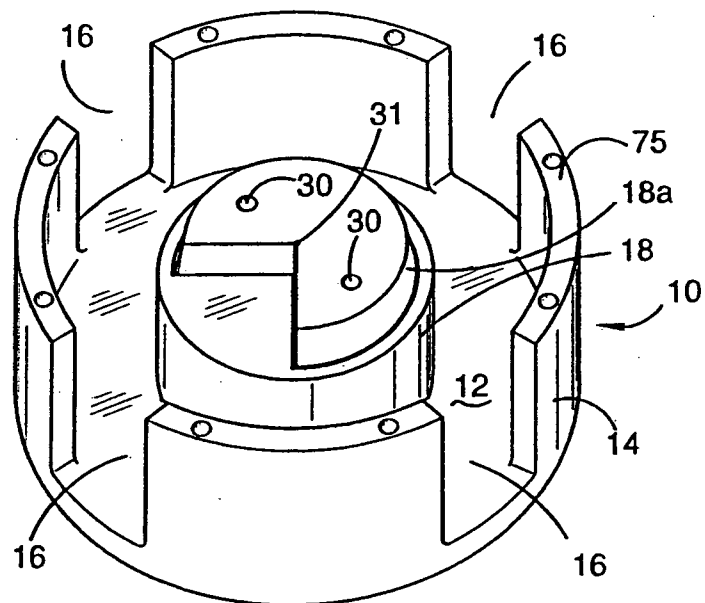


FIGURE 2

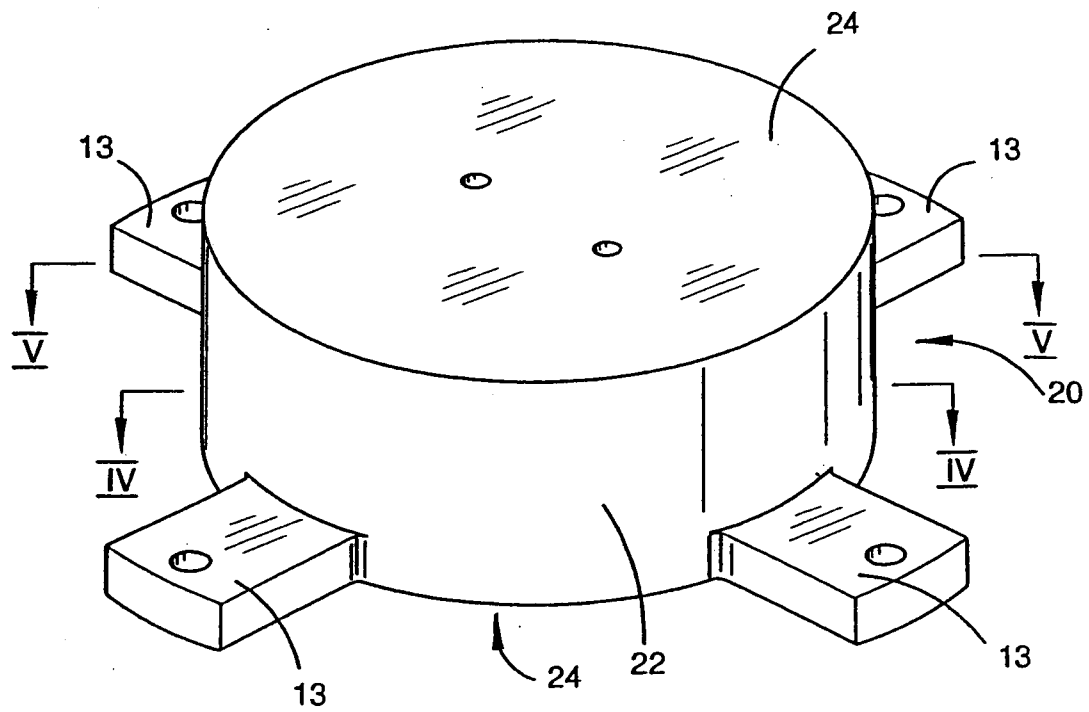


FIGURE 3

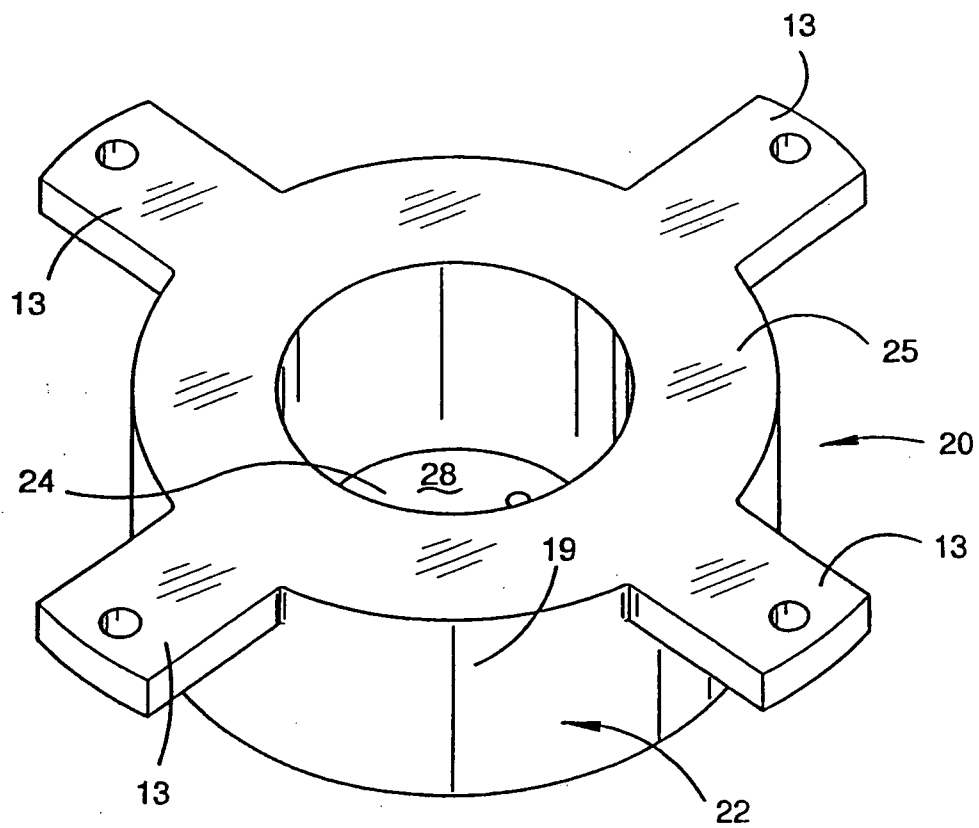
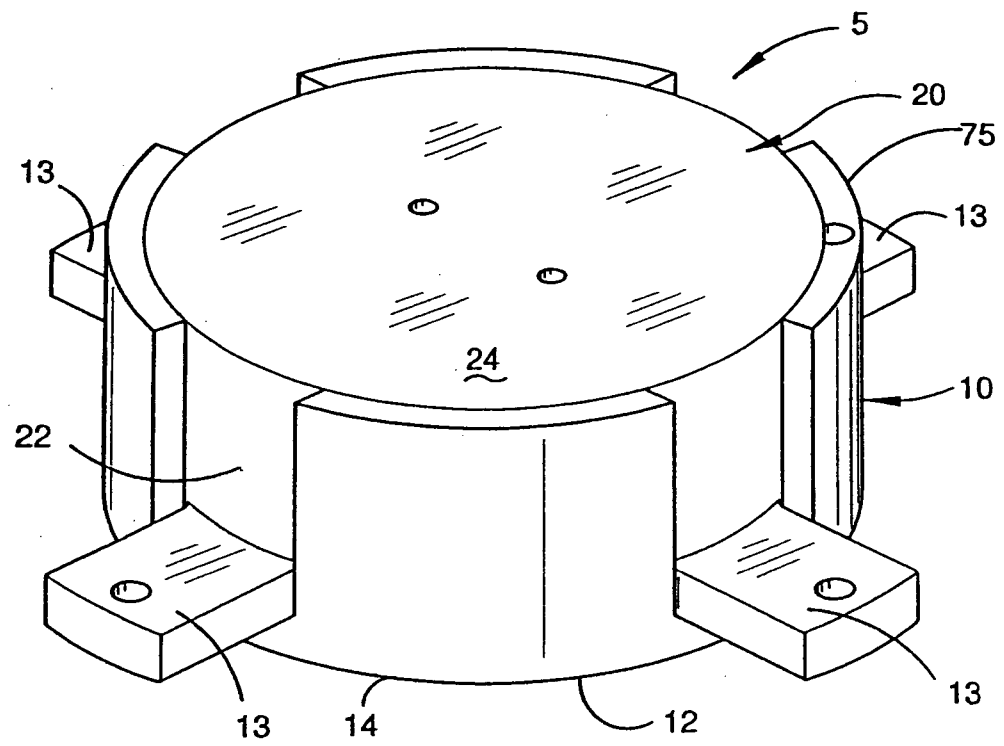


FIGURE 4



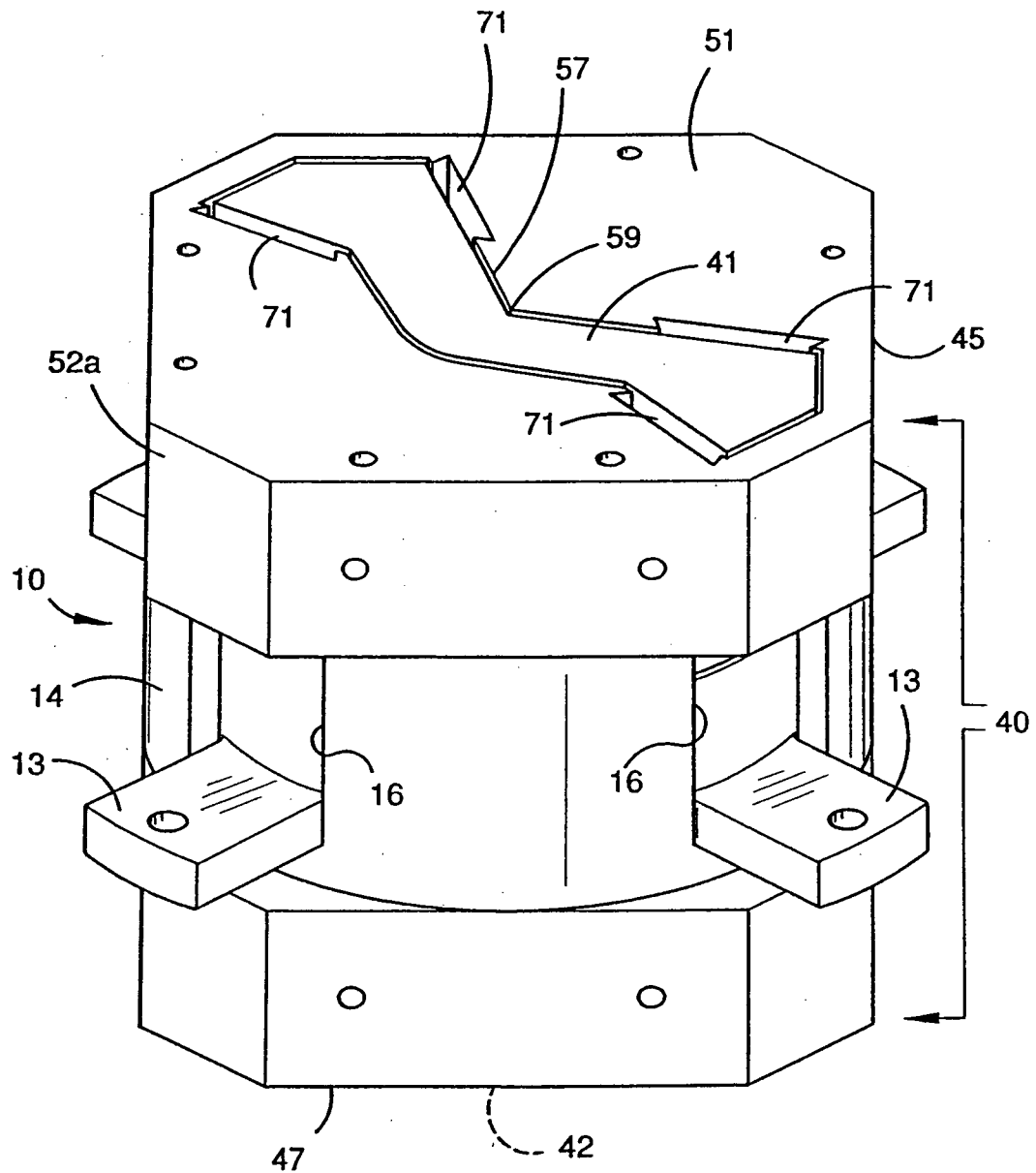


FIGURE 6

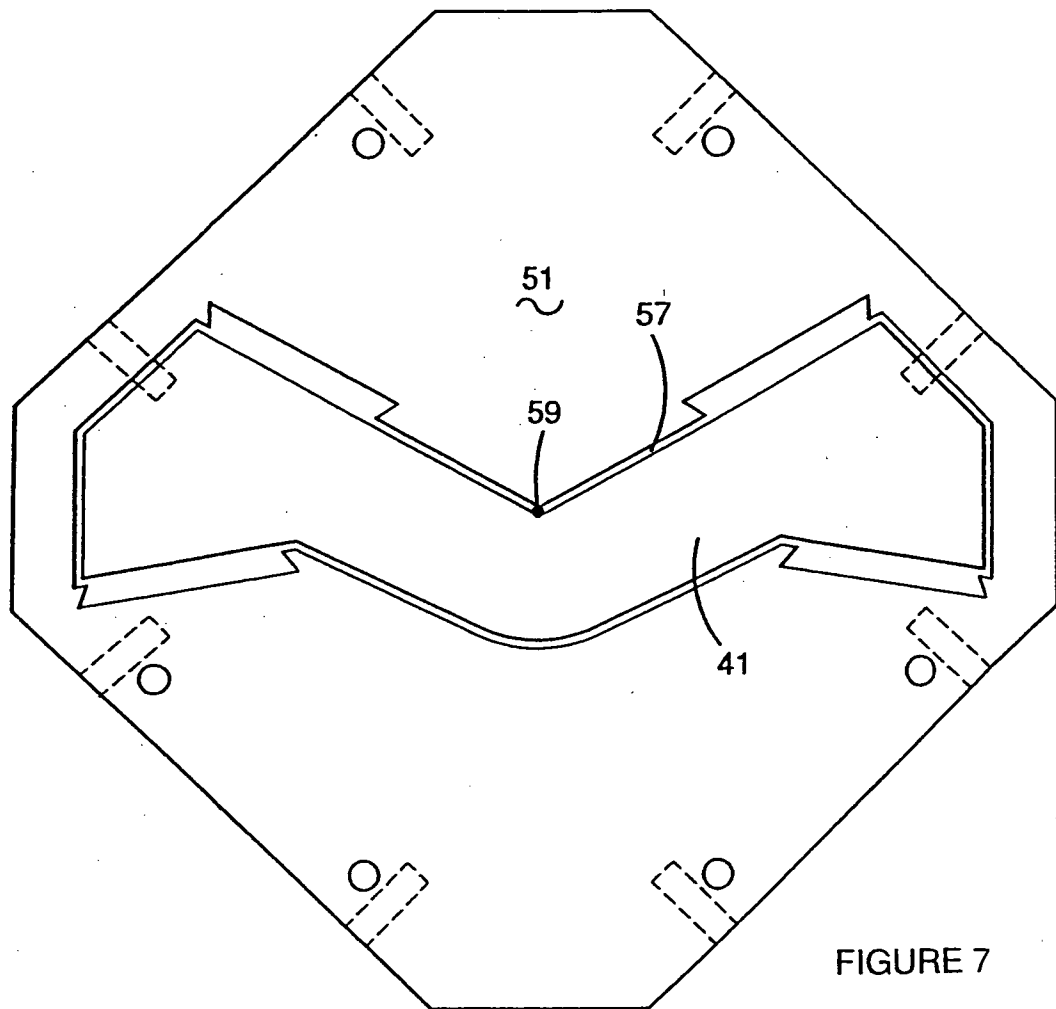


FIGURE 7

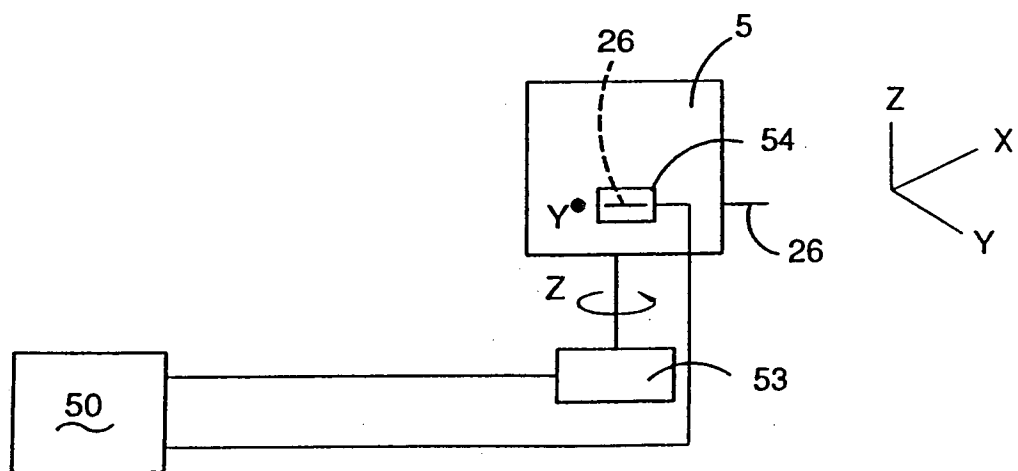


FIGURE 8

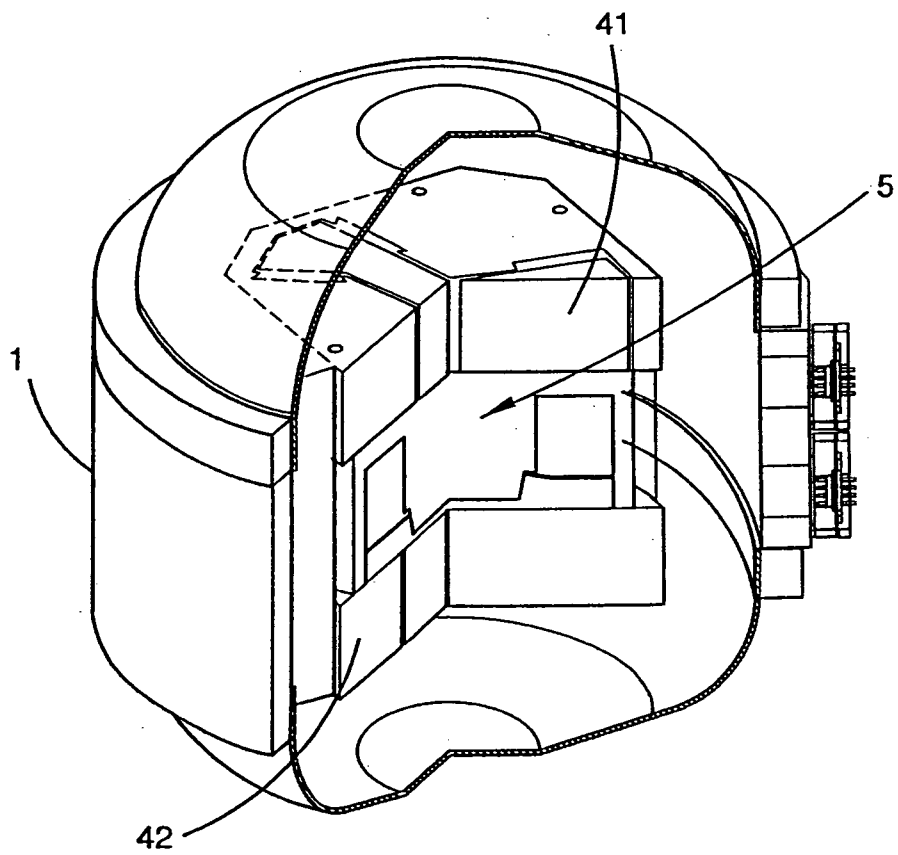


FIGURE 9

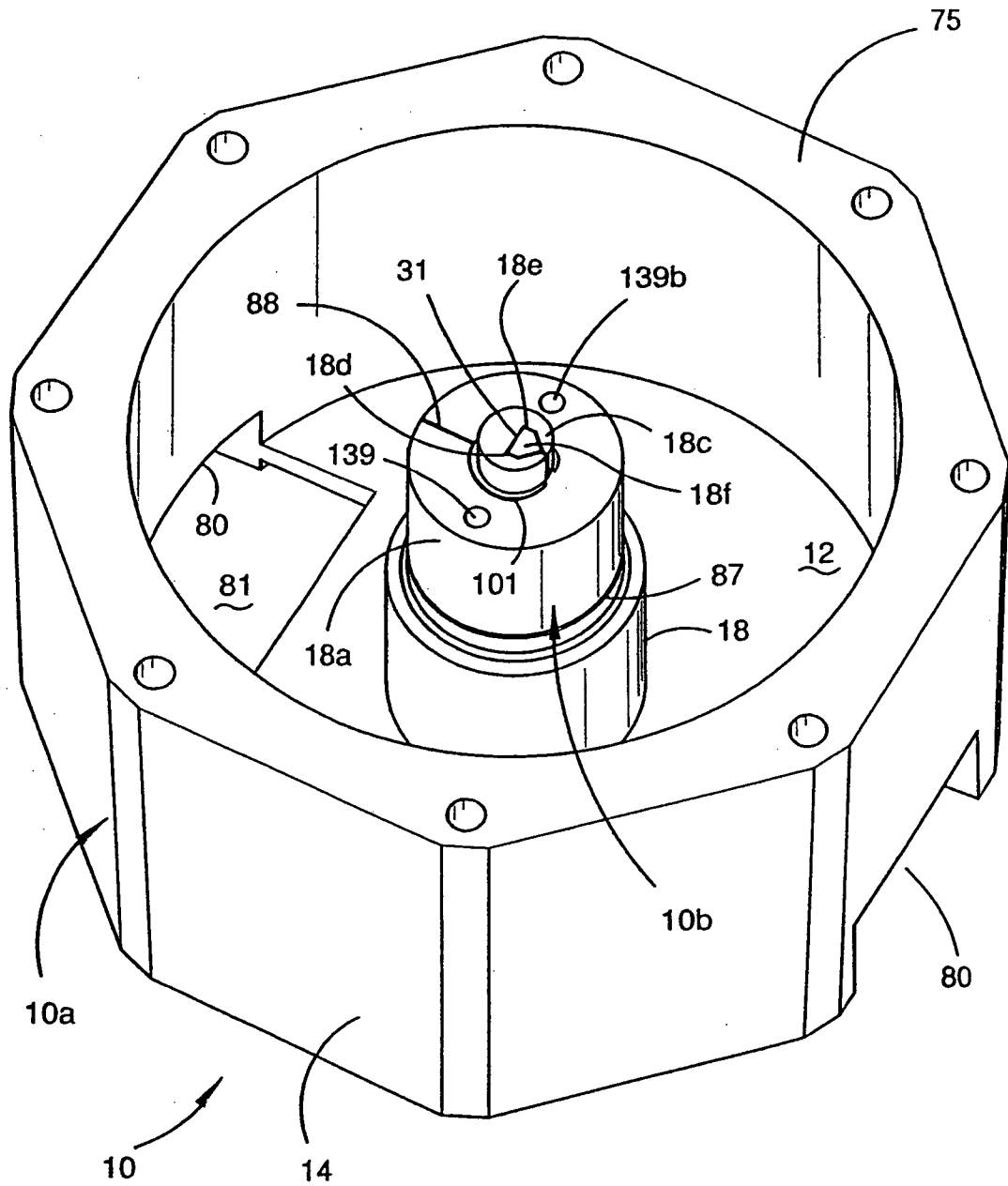


FIGURE 10

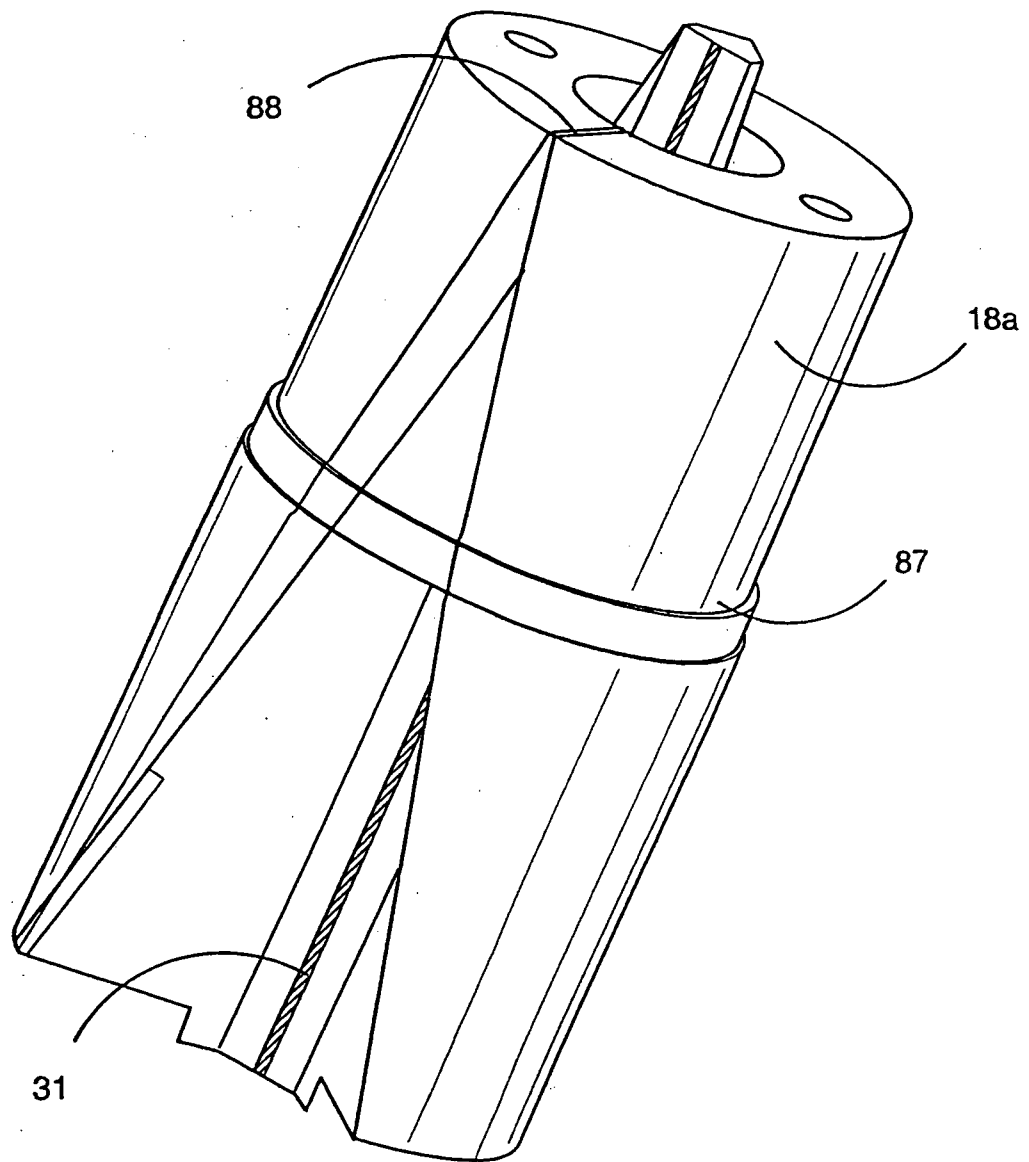


FIGURE 11

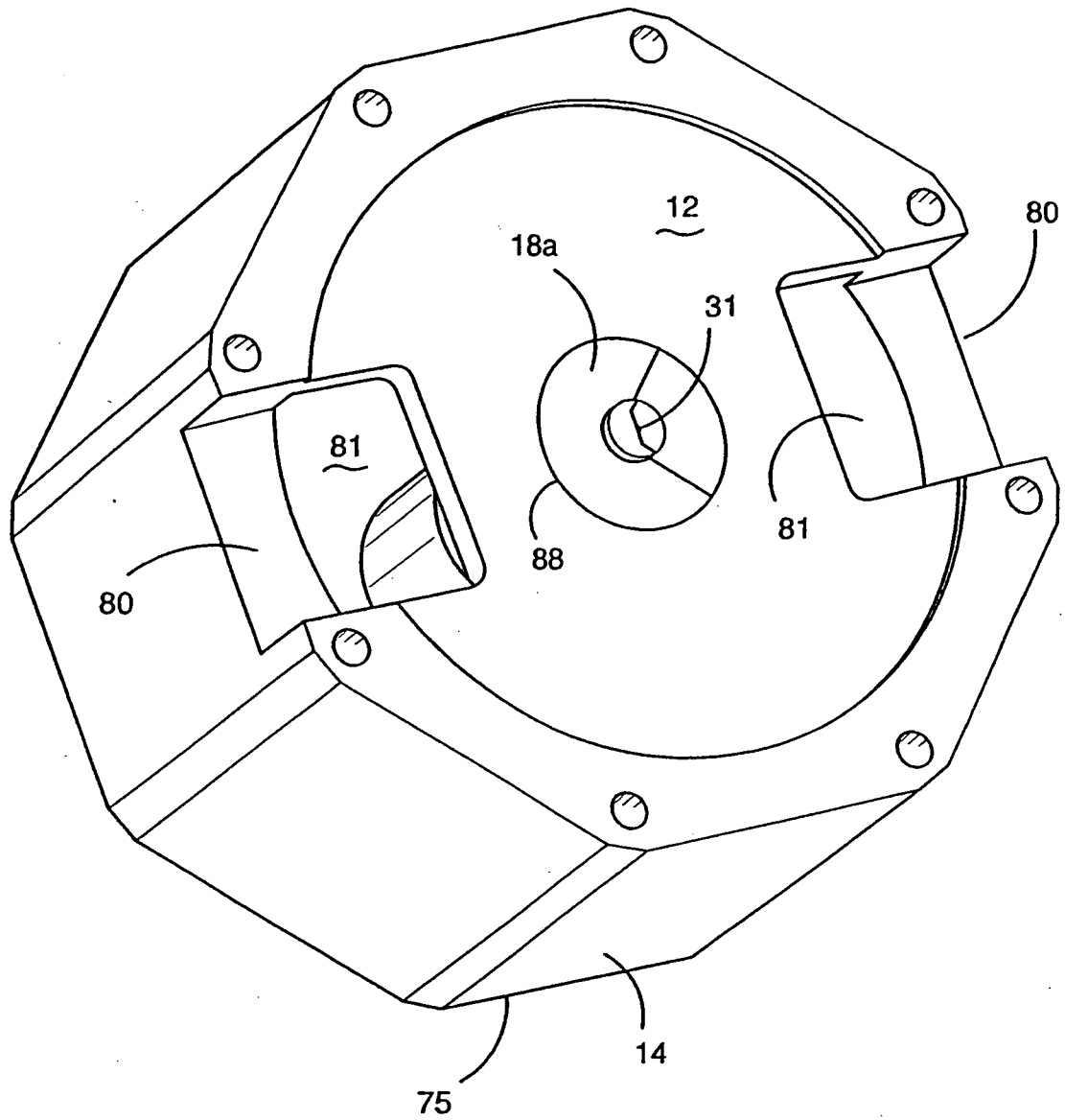


FIGURE 12

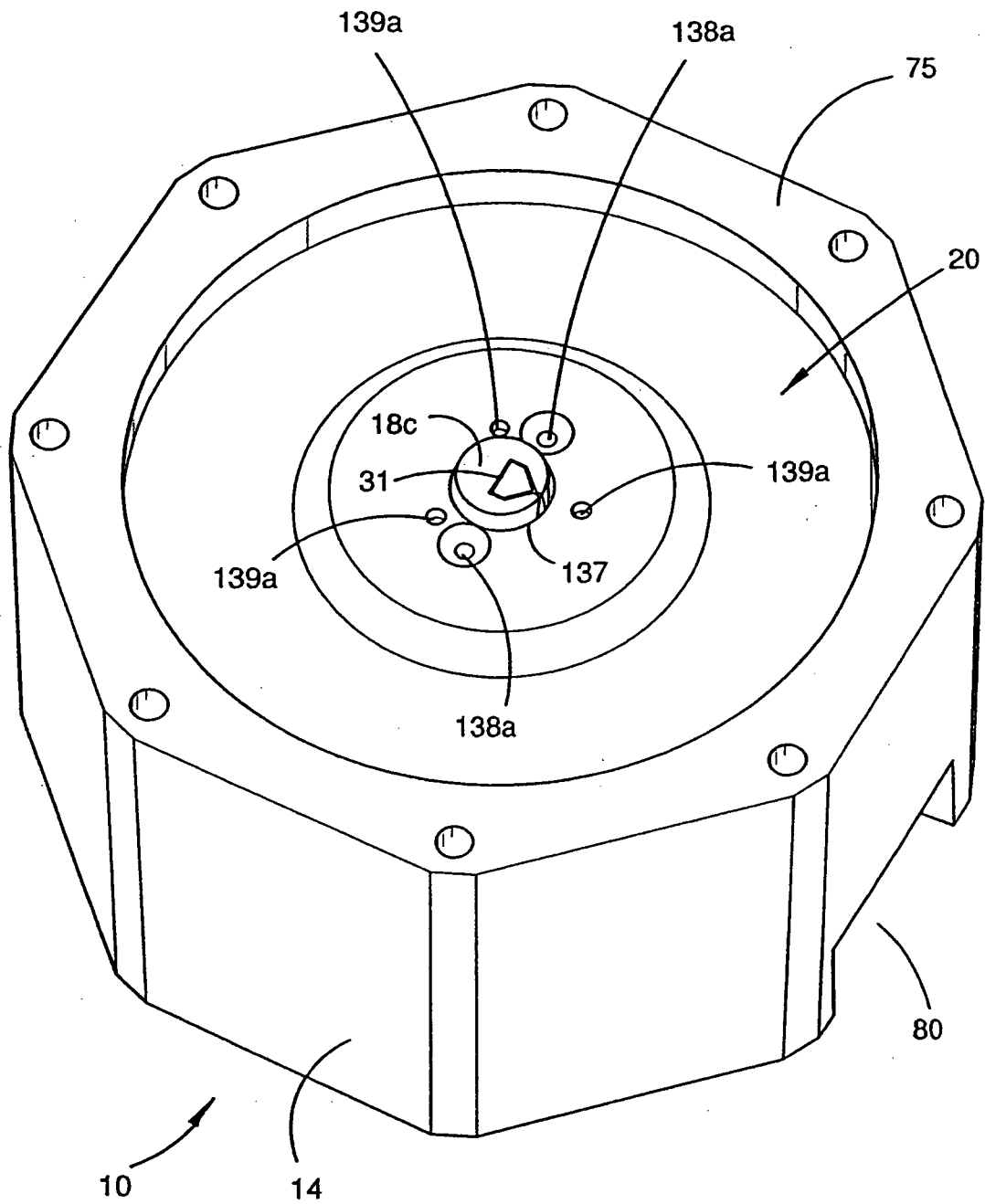


FIGURE 13

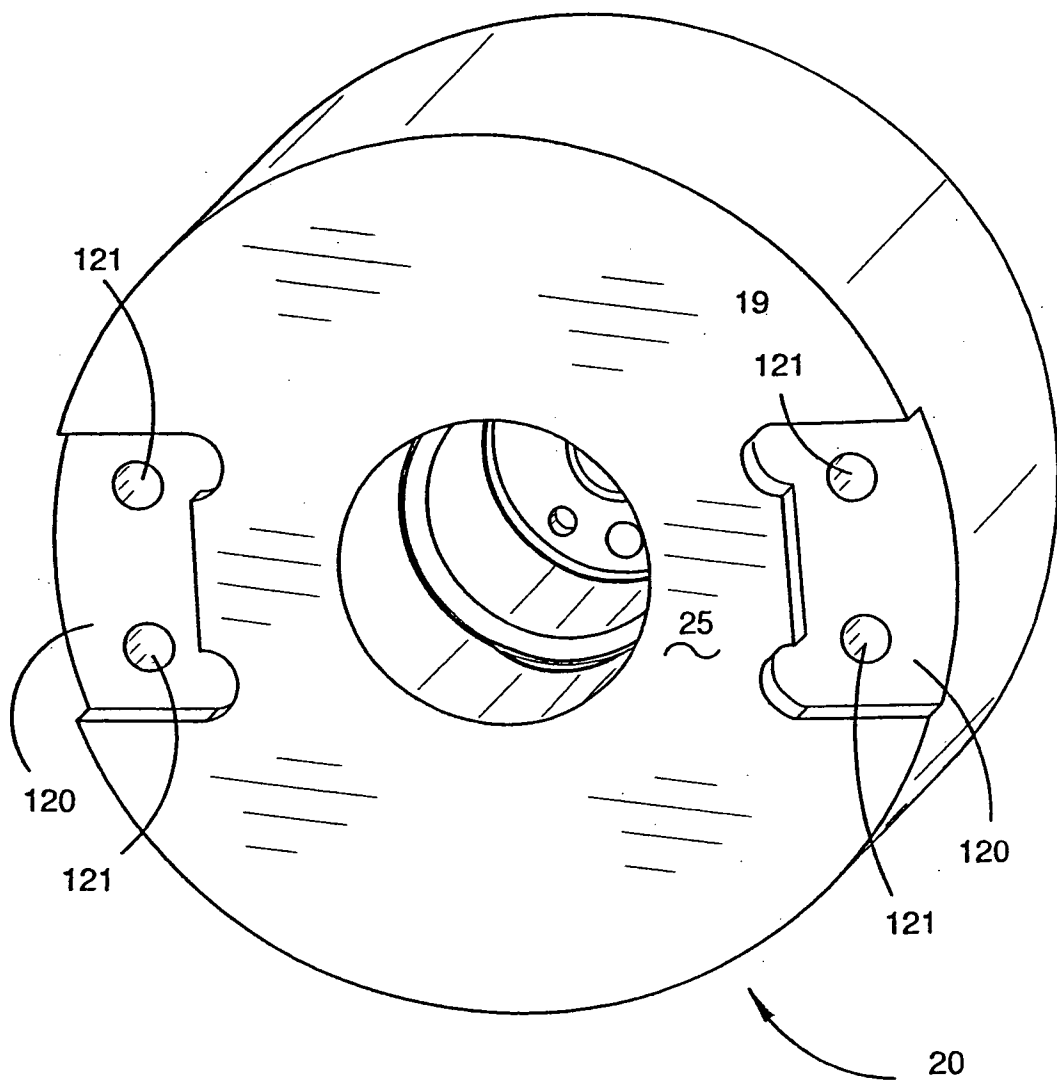


FIGURE 14

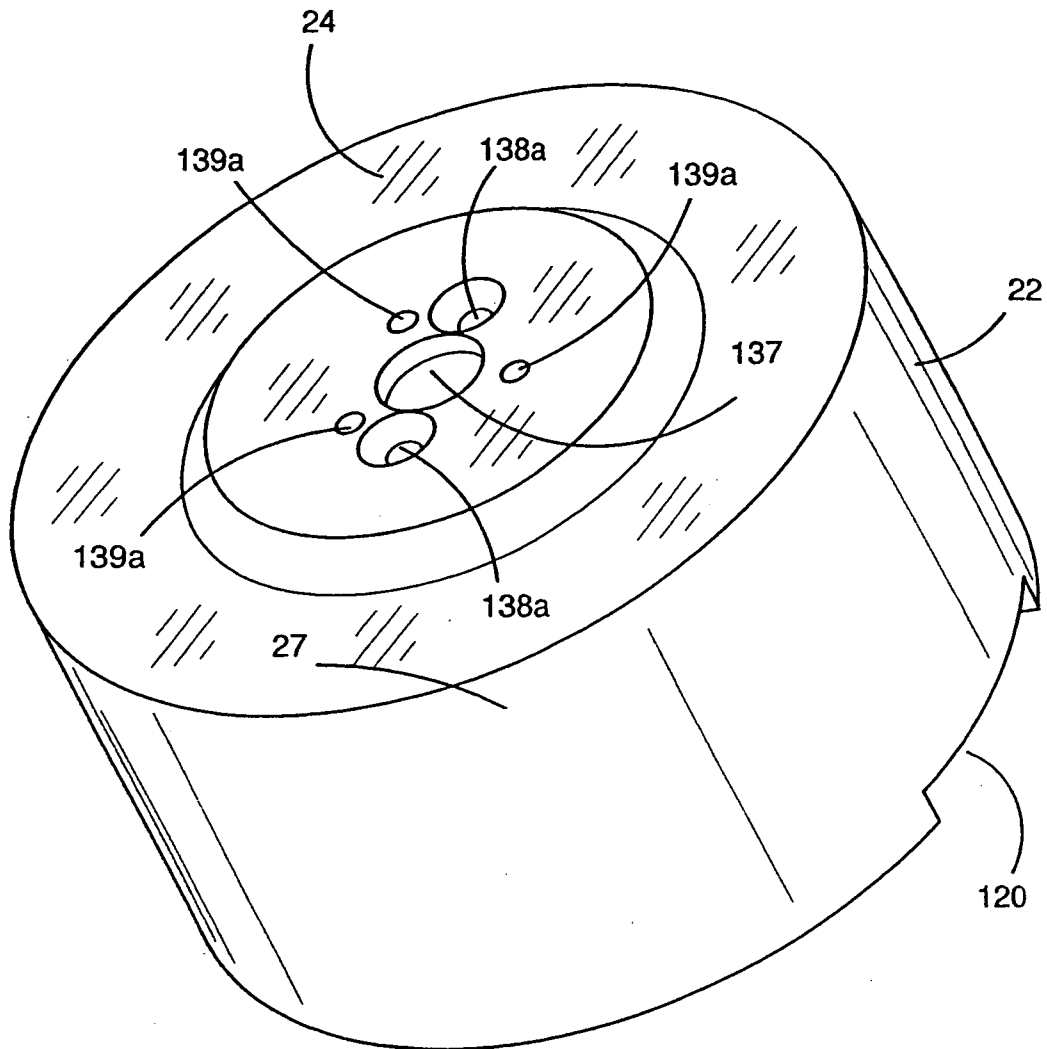


FIGURE 15

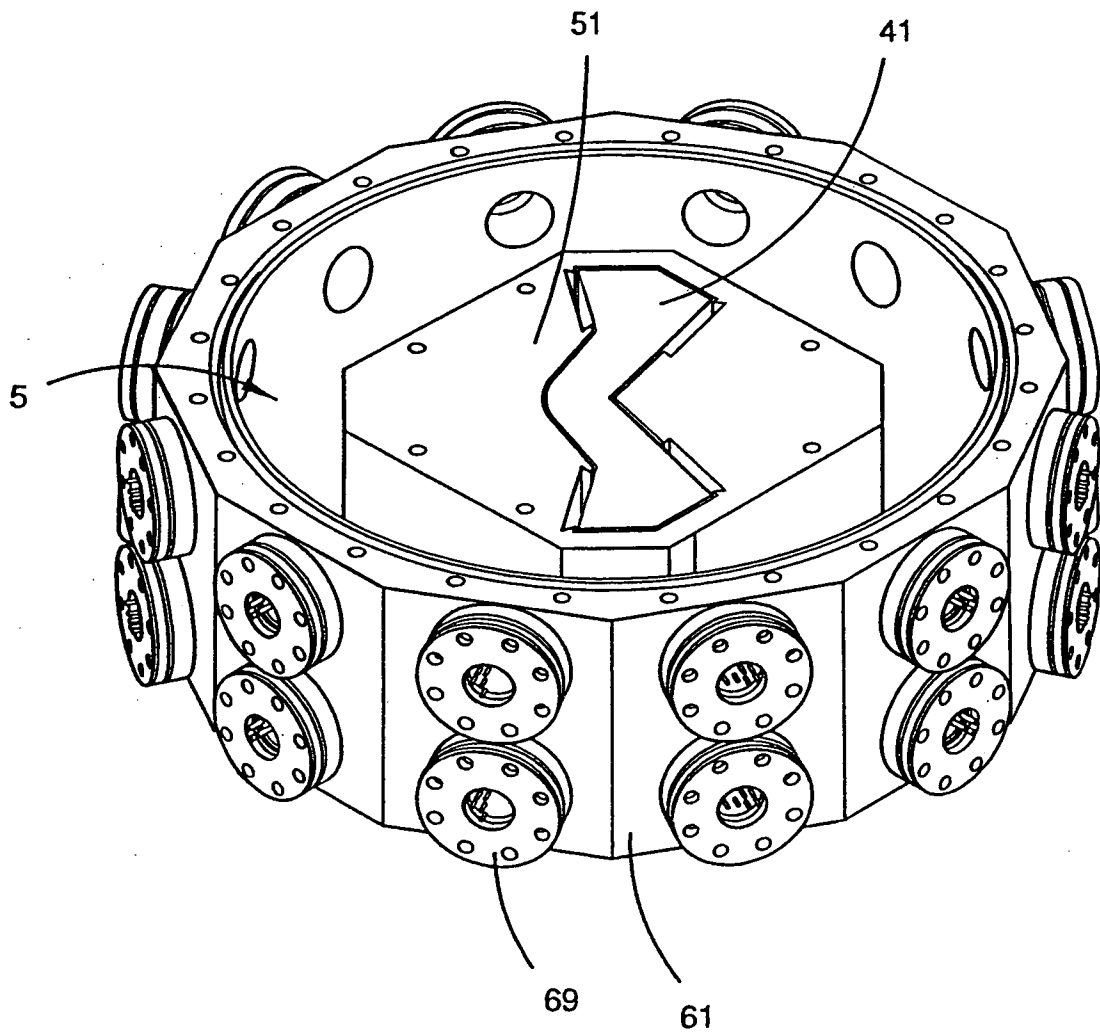


FIGURE 16

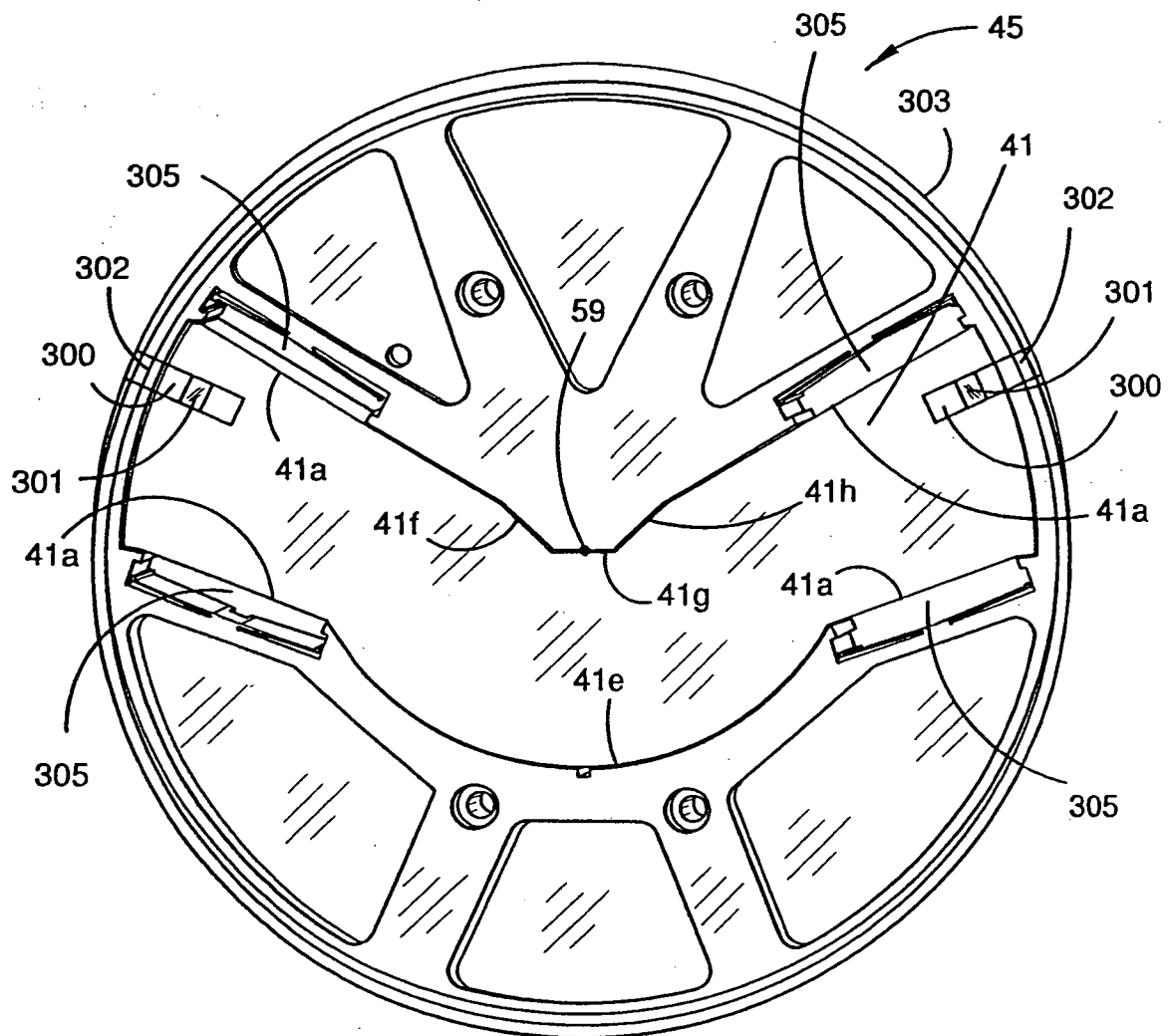


FIGURE 17

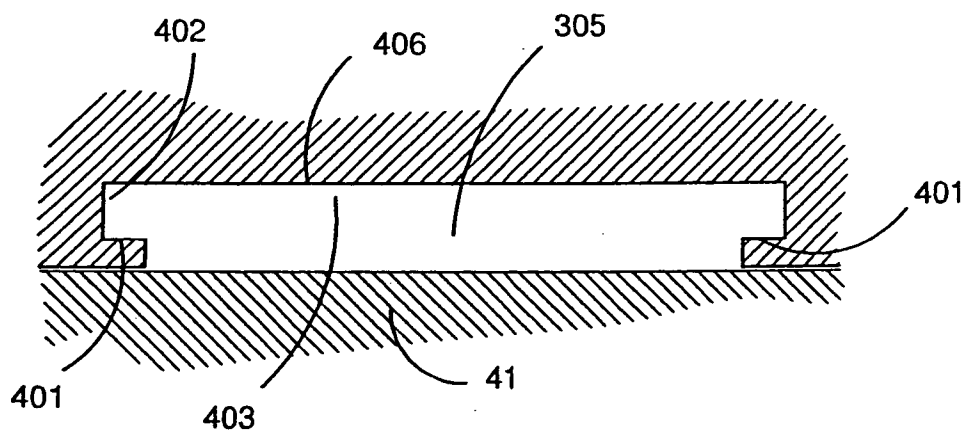


FIGURE 18

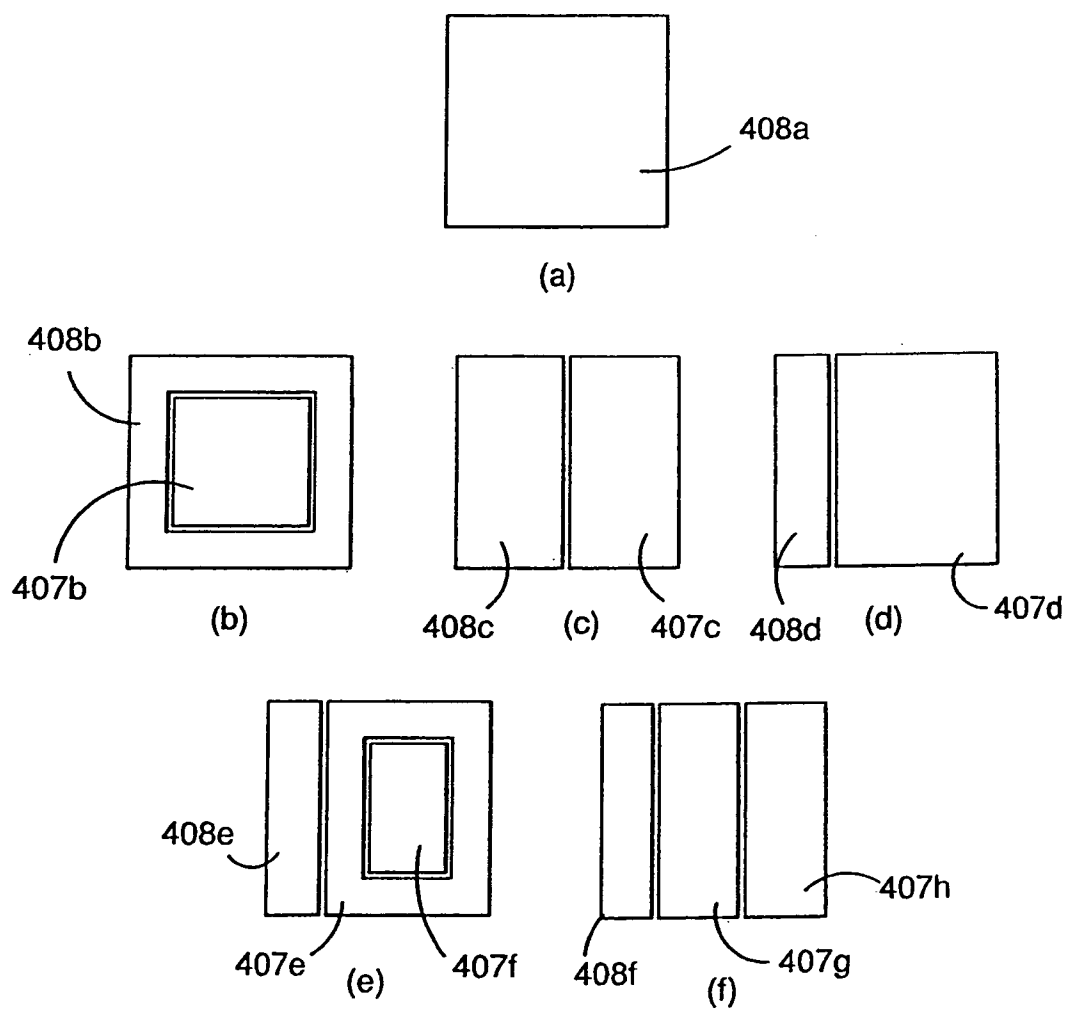


FIGURE 19

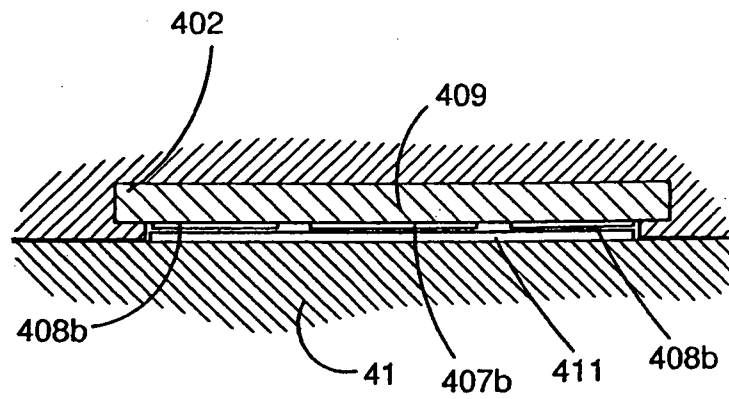


FIGURE 20

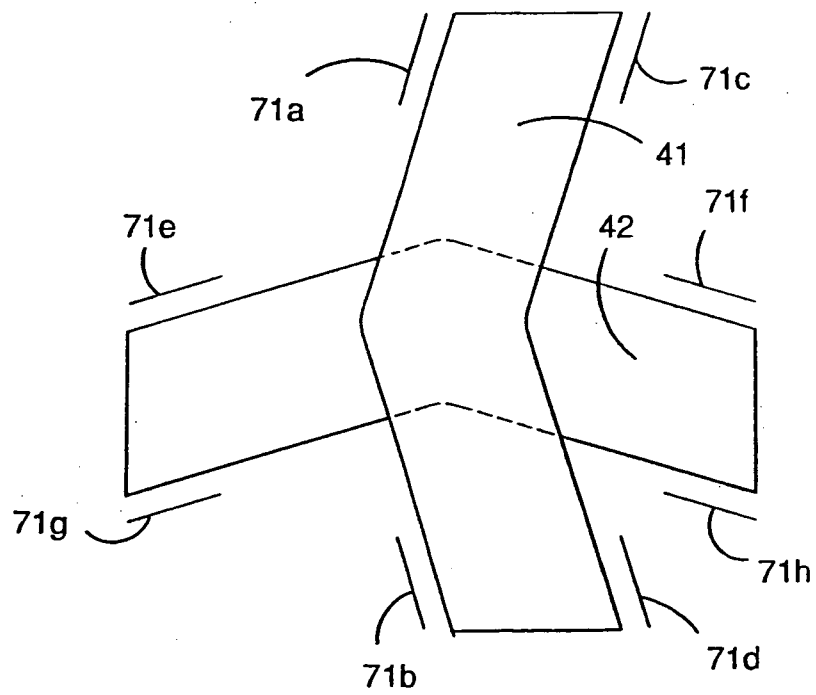


FIGURE 21

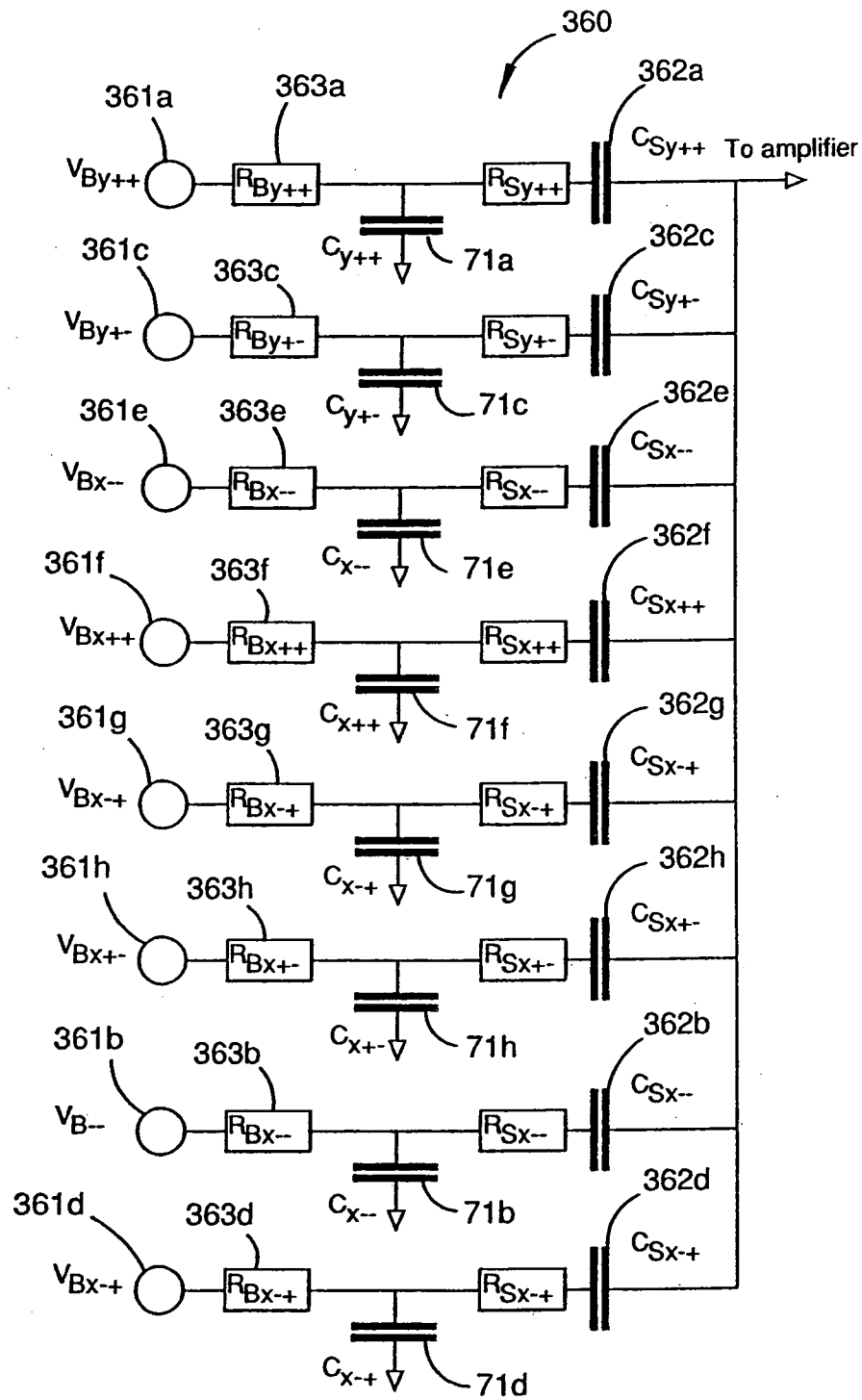


FIGURE 22 (a)

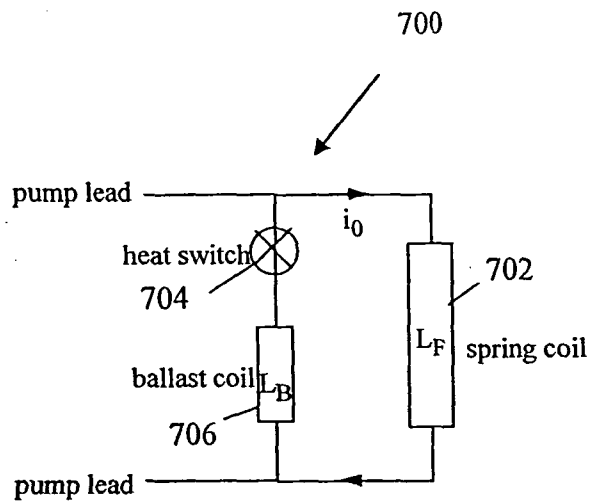


FIGURE 22 (b)

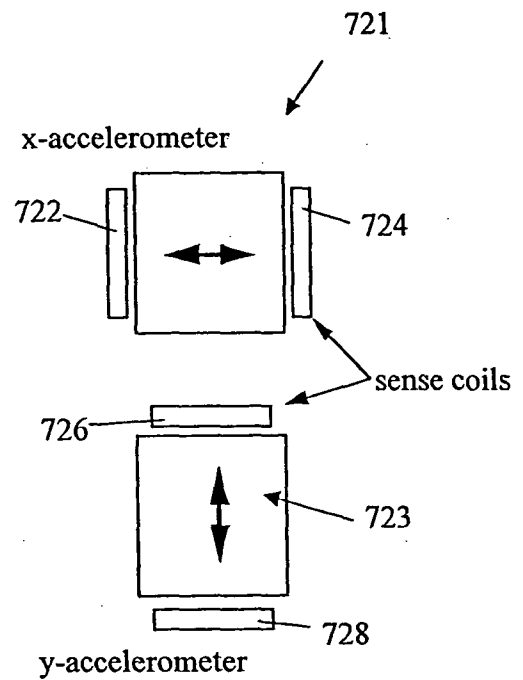


FIGURE 22 (c)

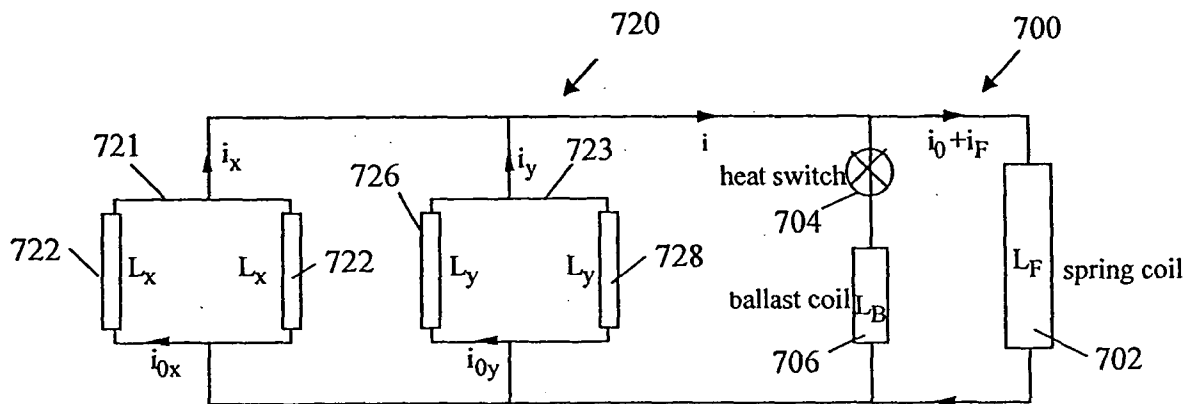


FIGURE 22 (d)

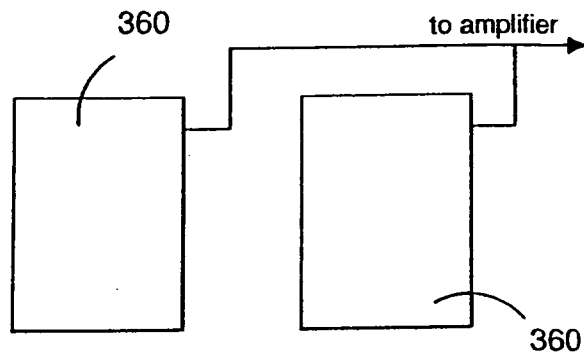
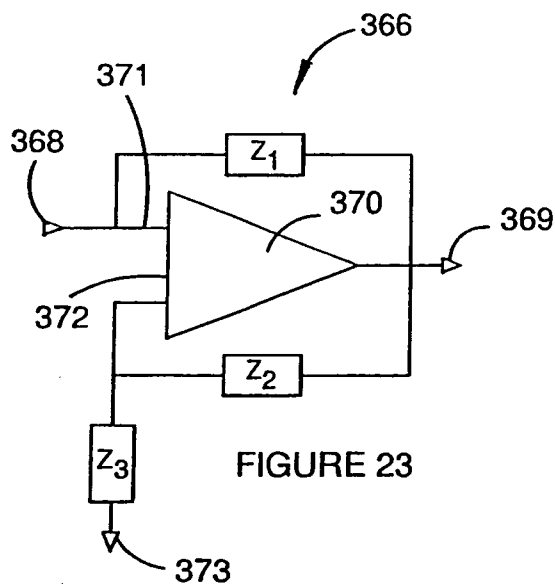


FIGURE 24

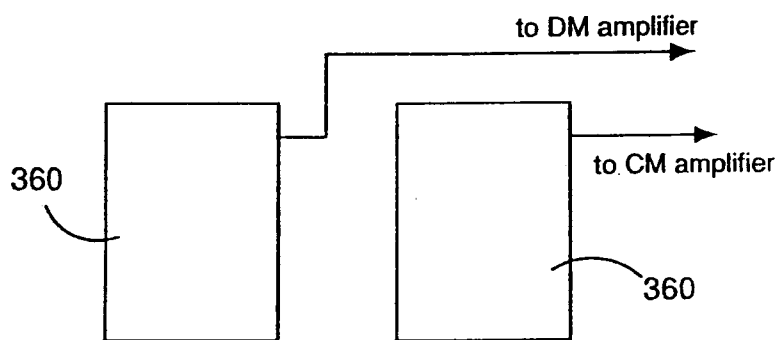


FIGURE 25

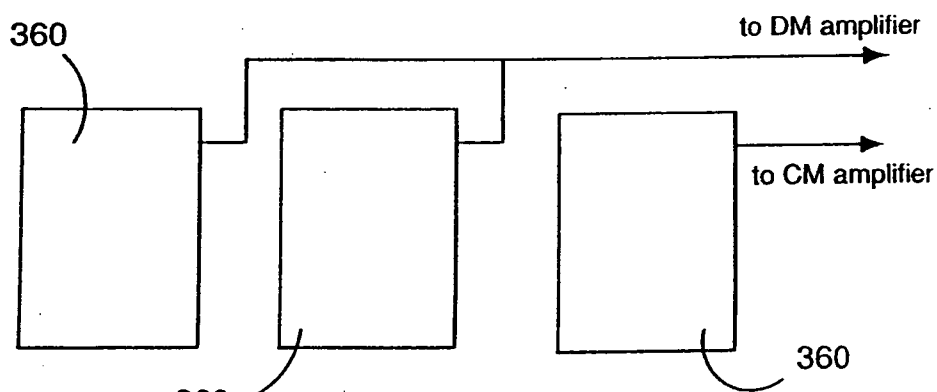


FIGURE 26

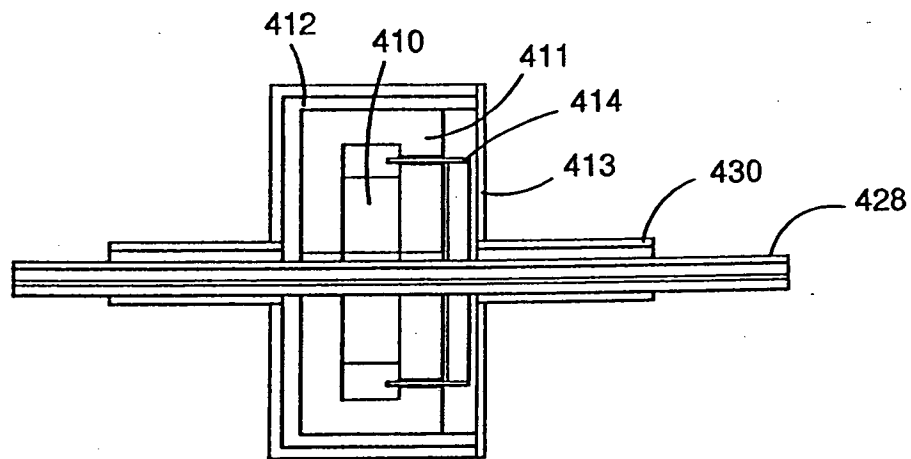


FIGURE 27

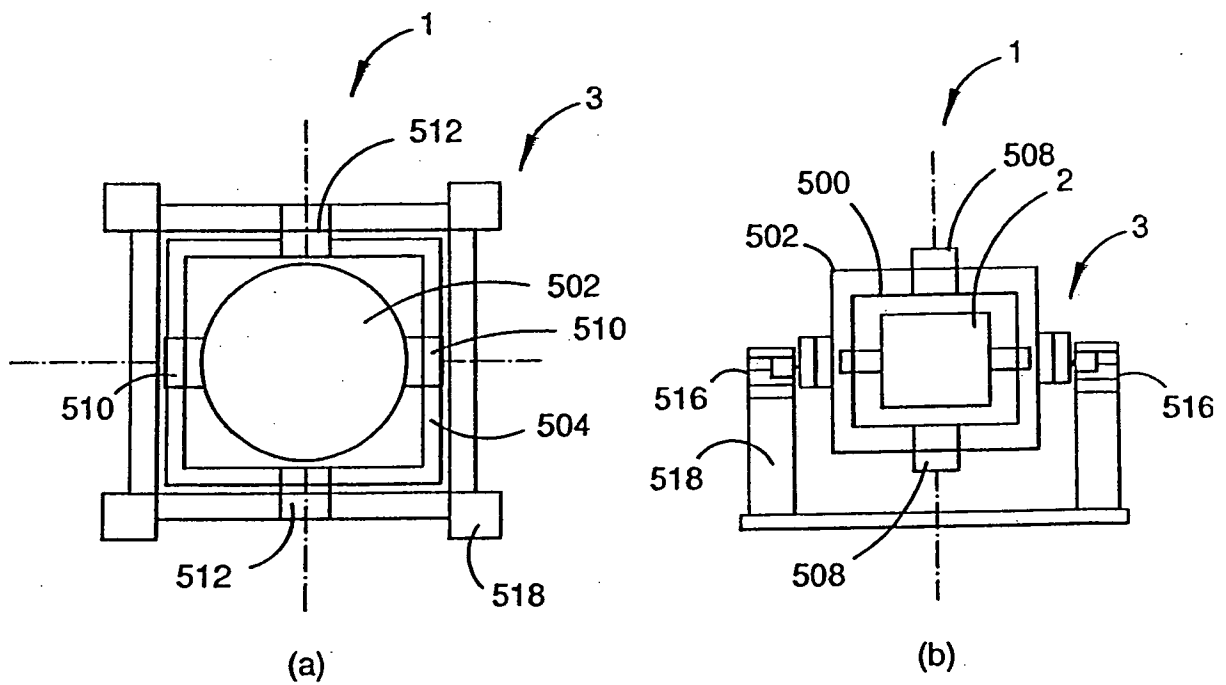


FIGURE 28

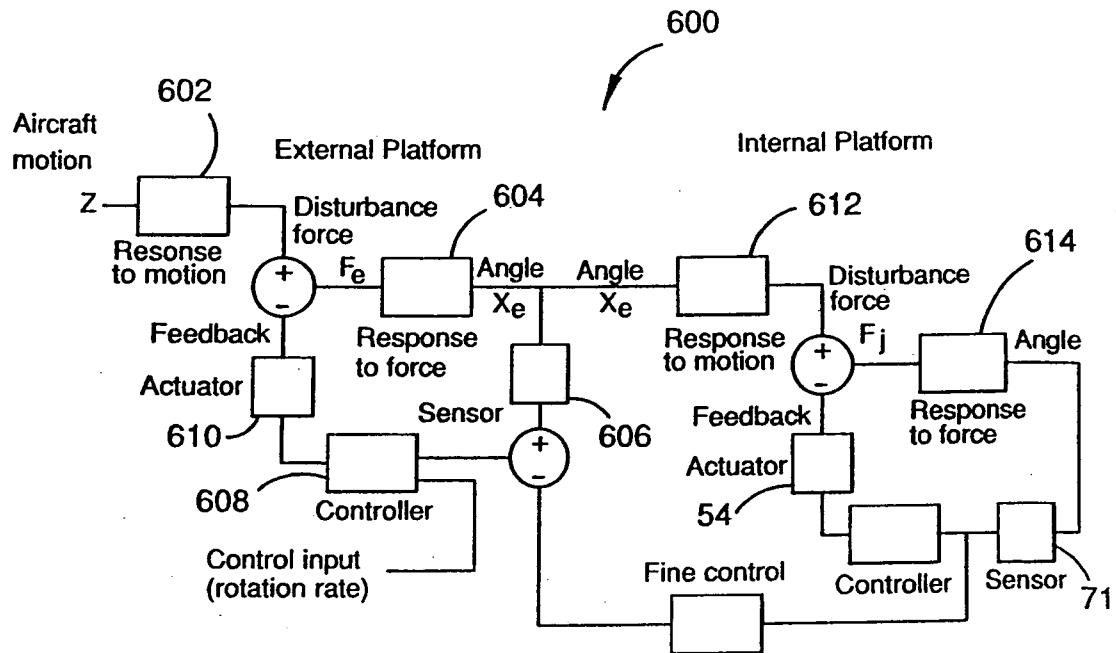


FIGURE 29

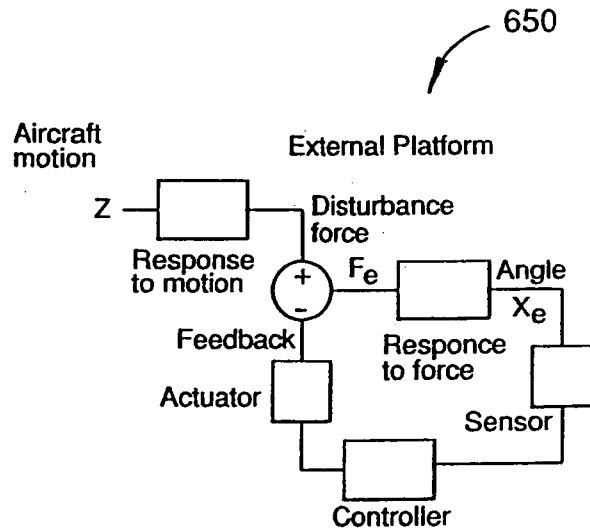


FIGURE 30

INTERNATIONAL SEARCH REPORT

International application No.

PCT/AU2009/001281

A. CLASSIFICATION OF SUBJECT MATTER

Int. Cl.

G01V 7/02 (2006.01)

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

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

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

WPI, EPODOC, INSPEC; IPC G01V 7/- & Keywords (gravity gradiometer, sensor mass, pivotable, acceleration, actuator, mass dipole moment, radius of gyration, flexure) and like terms.

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	WO 2008/061278 A1 (TECHNOLOGICAL RESOURCES PTY LTD) 29 May 2008 page 15, lines 9-33; page 25, lines 21-33; page 35, line 32 – page 36, line 2	
A	US 2006/0207326 A1 (MOODY et al) 21 September 2006 whole document	



Further documents are listed in the continuation of Box C



See patent family annex

* Special categories of cited documents:

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"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

24 December 2009

Date of mailing of the international search report

4 JAN 2010

Name and mailing address of the ISA/AU

AUSTRALIAN PATENT OFFICE
PO BOX 200, WODEN ACT 2606, AUSTRALIA
E-mail address: pct@ipaustalia.gov.au
Facsimile No. +61 2 6283 7999

Authorized officer

MELANIE O'BYRNE

AUSTRALIAN PATENT OFFICE
(ISO 9001 Quality Certified Service)

Telephone No : (02) 6283 2153

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/AU2009/001281

This Annex lists the known "A" publication level patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

Patent Document Cited in Search Report		Patent Family Member	
WO 2008061278	AR 062670	AU 2007249047	CA 2612602
	CL 25882007	EP 2089740	US 2008121036
	ZA 200710806		
US 2006207326	US 7305879		
Due to data integration issues this family listing may not include 10 digit Australian applications filed since May 2001.			
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