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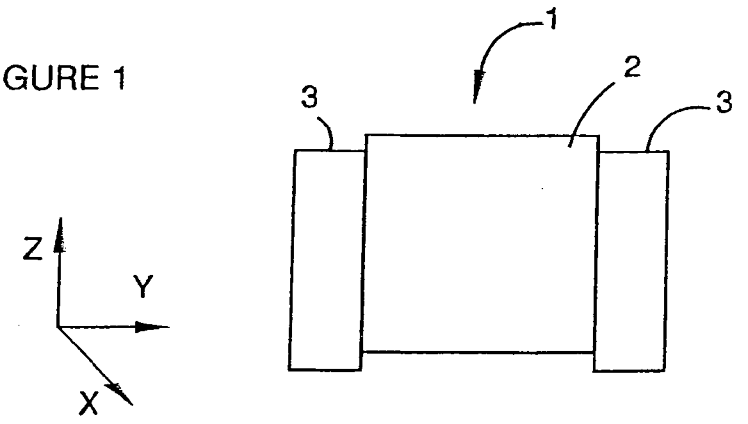
FIGURE 1



(57) Abstract: The present disclosure provides a method of detecting a change in gravity gradient using a gravity gradiometer. The gravity gradiometer comprises a detector for detecting the change in gravity gradient. The gravity gradiometer further comprises a sensor for generating a disturbance signal in response to an external disturbance. The method comprises the steps of exposing the gravity gradiometer to the external disturbance during operation of the gravity gradiometer. Further, the method comprises the steps of detecting the disturbance signal and receiving an output signal from the detector of the gravity gradiometer. The method also comprises the step of numerically correcting the output signal for an impact that a component of the gravity gradiometer experiences, as a consequence of the external disturbance using a response parameter that associates the external disturbance with a disturbance experienced by that component.

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GRAVITY GRADIOMETER WITH CORRECTION OF EXTERNAL DISTURBANCE

Field of the Invention

The present invention relates to a gravity gradiometer and to components for high precision measurement instruments.

Background of the Invention

Gravimeters are used in geological exploration to measure the first derivatives of the earth's gravitational field. 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 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 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.

Typically such devices have been used to attempt to locate deposits such as ore deposits including iron ore and geological structures bearing hydrocarbons.

The gravity gradiometer typically has at least one sensor in the form of sensor mass which is pivotally mounted for movement in response to the gravity gradient.

International publication WO 90/07131 discloses such a gravity gradiometer. Gravity gradiometers of that type are typically mounted in an aircraft and carried by the aircraft while making measurements. Consequently, the gravity gradiometer moves with movements of the aeroplane, which creates accelerations of the gradiometer. If the accelerations are not compensated for, they are detected by the gravity gradiometer and will produce noise or swamp a signal component that is associated with the actual the gravity gradient which is to be detected by the gravity gradiometer.

The gravity gradiometer disclosed in International publication WO 90/07131 includes two sensor masses which are orthogonally positioned and arranged to move about a common axis. The sensor masses are suspended by pivots and can oscillate in planes that are orthogonal to the common axis. For measurement of the gravity gradient the instrument is continuously rotated and a local change in the gravity gradient results in oscillating of both sensor masses relative to a rotated housing of the instrument. Such arrangement has the advantage that at least some unwanted accelerations, such as those resulting from a sudden movement of an aircraft, are experienced by both sensor masses in the same manner and can be eliminated.

However, the force that causes such an oscillation is very small and results in a very small signal that is indicative of the gravity gradient. The signal is typically accompanied by other much larger signals that are caused by sudden movements of an aircraft in which the gravity gradiometer may in use be positioned. Correction of an output of the gravity gradiometer for such other signal components in a satisfactory manner is a technological challenge.

Summary of the Invention

The present invention provides method of detecting a change in gravity gradient using a gravity gradiometer, the gravity gradiometer comprising a detector for detecting the change in gravity gradient, the gravity gradiometer further comprising a sensor for generating a disturbance signal in response to an external disturbance, the method comprising the steps of:

exposing the gravity gradiometer to the external disturbance during operation of the gravity gradiometer;

detecting the disturbance signal;

receiving an output signal from the detector of the gravity gradiometer; and

numerically correcting the output signal for an impact that a component of the gravity gradiometer experiences as a consequence of the external disturbance using a response parameter that associates the external disturbance with a disturbance experienced by that component.

The gravity gradiometer typically comprises a large number of portions that are moveable relative to each other. Consequently, the external disturbance, such as a disturbance force or motion associated with a sudden movement of an aircraft in which the gravity gradiometer may be positioned, may be experienced differently by different portions of the gravity gradiometer. The output signal of the gravity gradiometer may be a signal that is indicative if the gravity gradient. Embodiments of the present invention enable correction of the output of the gravity gradiometer for the external disturbance in a relatively accurate manner.

The response parameter typically is dependent on a mechanical responsiveness of the component to the external disturbance.

The gravity gradiometer may comprise a support structure that supports the detector and that is arranged to attenuate an impact of the external disturbance on the detector and wherein the component is a part of the detector.

The method may comprise correcting the output signal by applying a correction force, the correction force being correlated with the external disturbance, wherein the correction force reduces an impact of the external disturbance and the output signal is then numerically corrected for at least a portion of a remaining impact of the external disturbance on the output signal.

In one embodiment the method comprises the steps of:

applying an external force to the gravity gradiometer;

detecting the external force;

analysing if the component of the gravity gradiometer experiences a force that is correlated with the external force; and, if the correlation has been identified; and

calculating the response parameter.

The component may include the detector of the gravity gradiometer and the step of analysing if the component of the gravity gradiometer experiences a force that is correlated with the external force may comprise receiving a detector signal that includes the gravity gradient signal and analysing if that signal is correlated with the detected external force.

Alternatively or additionally, the method may comprise calculating the response parameter numerically using a mathematical model that represents a mechanical responsiveness of the component.

In one embodiment the sensor for generating a disturbance signal is one of a plurality of sensors for generating disturbance signals and the method may comprise detecting a plurality of the disturbance signals in response to the external disturbance wherein each sensor is arranged to detect at least one of: a force associated with a rotation about one of three orthogonal axes and a force associated with a motion along one of three orthogonal axes.

The disturbance may also be an electromagnetic disturbance and the sensor for generating a disturbance signal may generate a signal in response to the electromagnetic disturbance.

The method typically is operated by a feed-forward control arrangement for reducing transmission of the external disturbance to the component of the gravity gradiometer.

The gravity gradiometer typically comprises a support structure and a pivot that couples the detector including the component to the support structure wherein the response parameter is dependent on an equivalent spring constant of the pivot.

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.

Brief Description of the Drawings

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

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;

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 bar 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 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 bar according to a further embodiment 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 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 circuits of Figures 22;

Figure 22 is a circuit diagram relating to a specific embodiment of the invention;

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

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;

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 specific embodiment of the present invention.

Detailed Description of the Specific Embodiments

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. Throughout this specification the ground plane coincides with an x-y plane of an x,y,z-coordination system and consequently the gravity gradiometer is in this embodiment arranged for orientation along the z-axis so that the Γ_{xy} and $(\Gamma_{xx}-\Gamma_{yy})$ components of the gravity 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 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 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. For further details on the general principal of 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 housing 2 which is connected to mount 3 for connection to an external platform (not shown). The external platform is arranged for rotation of the housing 2 at a suitable angular frequency about the z-axis. Further, the external platform is arranged for adjusting the housing 2 about three orthogonal axes.

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 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 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 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.

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 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 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 provided by the external platform.

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

The bar 41 is formed in a first housing portion 45 and the bar 42 is formed in a second housing portion 47. The bar 41 and the second housing portion 45 is the same as bar 42 and the second housing portion 47 except that one is rotated 90° with respect to the other so that the bars 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 bar 41 is formed by a cut 57 in the wall 51 except for a second flexure web 59 which joins the bar 41 to the wall 51. The second flexure 59 web is shown enlarged in the top view of the bar 41 in Figure 7. Thus, the bar 41 is able to pivot relative to the first housing portion 45 in response to changes in the gravitational field. The bar 42 is mounted in the same way as mentioned above and also can pivot 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 bar 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 bars and for producing output signals indicative of the amount of movement and therefore of the measurement of the differences in the gravitational field sensed by the bars.

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 bars 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.

The transducers 71 measure the angle of displacement of the bars 41 and 42 and control circuitry (not shown) is configured to measure the difference between them.
In this embodiment, the transducers 71 are constant charge capacitors, which will be described in more detail with reference to Figure 22.

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 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 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 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 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 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.

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 bar 41 is connected to the rim 75 of the first 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.

Thus, 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.

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.

The first housing portion 45 supports bar 41 in the same manner as described via flexure web 59 which is located at the centre of mass of the bar 41. The bar 41 is of chevron shape, although the chevron shape is slightly different to that in the earlier 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 bar 41 have screw-threaded bores 300 which receive screw-threaded members 301 which may be in the form of 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 plugs 301 can be screwed into and out of the bore 300 to adjust their position in the bore to balance the mass 41 so the centre of gravity is at the flexure web 59.

As drawn in Figure 17, the bores 300 are 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.

Figure 17 also shows openings 305 for receiving a portion of the transducers 71 for monitoring the movement of the bar 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 is mounted to the bar 41 and another capacitor plate is stationary relative to the bar 41 so that a gap is defined between the capacitor plates. Movement of the bar changes the gap which in turn changes a voltage across the constant charge capacitor.

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.

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 bars 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 comprises two separate capacitor elements 408b and 407b which are not in electrical contact. Again, the first electrode is provided by the sensor bars 41 or 42, which are at ground potential. The capacitor element 408b 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 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 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.

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

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 on insulating body 409. The plate 411 is metallic and positioned on the bar 41. In this embodiment plate 411 provides one capacitor element that opposes capacitor elements 407 b and 408 b. In this case the bar 41 may be of relatively low electrical conductivity or may be electrically insulating.

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

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

As will be apparent from Figure 21, four transducers 71 are arranged adjacent the ends of the bar 41. The second housing portion 47 also has four transducers arranged adjacent the bar 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 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 capacitor electrode is in this embodiment provided by a surface the sensor bars 41 or 42. For example, each transducer 71a - 71e may have a second electrode of the type as shown in Figure 19.

Oscillating movement of the sensor masses 41 and 42 results in a movement of the first capacitor electrodes (surfaces of the sensor bars 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. In this case, 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 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 bars 41 and 42, which are in this embodiment 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 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 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. 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 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.

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

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 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.

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 1GΩ or more, and are arranged for substantially preventing flow of charges and thereby providing for the component transducers 71a to 71e to 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 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 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 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, "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.

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.

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.

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.

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

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 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 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 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 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 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 Z1, Z2 and Z3. The low noise amplifier 370 has two input 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 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

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

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

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 amplifiers noise matched resistance is a few 1MΩ.

Further, the amplifier 370 has a noise temperature $T_{opt}=\frac{\sqrt{S_V S_i}}{2k_B}$ (k_B: Bolzman constant) of less than 1K.

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

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

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 senor masses 41 and 42 and f_o is the resonance frequency. The noise density S_Γ 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 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 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 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 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 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.

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 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.

As described above, one or both of the bars 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 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 2 that is rotated by an external mounting about a z-axis. The external mounting 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 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 rotable about the x-axis by x-drive 510, which includes bearings and the outer stage 504 is rotable 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.

The external mount 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 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.

The external mounting 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 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.

Figure 29 shows a block diagram 600 that illustrates how the common mode signal, generated within the housing 2 ("internal platform"), is used for rotational z-axis correction of the external support structure ("external platform").

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 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 two inputs.

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

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

where H_f and H_z are constants.

Equation 3 may be written as

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

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 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 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.

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 described above.

In the above-described embodiment the gravity gradiometer 1 is arranged so that rotation about the z-axis is controlled to a fixed uniform rotation speed. The input signal for controlling the motion is provided by the IMU 606 and directed to the controller 608. However, the IMU 606 may only have limited accuracy at the 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 transducers 71 is used for fine-tuning. This same signal is also used inside the internal platform in a feedback loop to stabilise the instrument against applied angular acceleration (via actuator 54). The specification for this internal feedback system is stringent and to ease this requirement, some of the burden is transferred to the external platform in that manner.

In a variation of the above-described embodiment the IMU may also be used in a feed-forward configuration.

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 elements of Figure 30 were already described above and function in an analogous manner to inhibit rotation about the x- and y- axes.

Referring now to Figure 29, a method of correcting an output from the gravity gradiometer in accordance with a specific embodiment of the present invention is now described. As described above, external disturbance forces, such as forces that are associated with sudden impacts on an aircraft in which the gravity gradiometer 1 is positioned, cause equivalent forces K_e Z on components of the gravity gradiometer. For example, the equivalent force K_e Z may be measured by an IMU. The output signal of the gravity gradiometer 1, in this embodiment the output signal of the transducers sensors 71, is corrected for an impact by such external forces.

The external disturbance forces and the equivalent forces as experienced by a component if the gravity gradiometer (the component may for example be the internal platform including the gravity gradient detector or the IMU on the external platform) are related to each other by the above mentioned respective constants K_e, which in this embodiment are determined as follows. The gravity gradiometer 1 is initially exposed to an external force and an equivalent disturbance force is then measured for example by one of the IMUs. The constant K_e is determined from the ratio of the external force and the measured equivalent force. Alternatively or additionally, the constants K_e are determined using a mathematical model that models a mechanical responsiveness of the component to the external force.

In this embodiment the motion of the gravity gradiometer 1 is corrected for components of an external disturbance force in three orthogonal directions and for rotation about three orthogonal axes. Consequently, the motion of the gravity gradiometer 1 is corrected for 6 degrees of freedom. The gravity gradiometer 1 comprises a plurality of sensors (such as the IMUs and the transducer sensors 71) and is arranged so that motions for each one of the 6 degrees of freedom are detected. For each degree of freedom it is initially investigated if the respective component of the applied external force causes an equivalent component force that is correlated with that component of the external force. Once a correlation has been identified, for example between the external force and an output signal of the gravity gradient detector as detected by the transducer sensors 71, respective constants K_{ei} (i= 1,2,3,4,5 or 6) are then obtained mathematically and/or from the ratio of the measured components of the equivalent disturbance force and the respective components of the external disturbance force. In this example the external disturbance is a mechanical disturbance. However, it will be appreciated that in an alternative example the external disturbance may be an electrodynamic disturbance and the gravity gradiometer may comprise a disturbance sensor that generates an electrical signal in response to a detected electromagnetic disturbance.

In use of the gravity gradiometer 1 the output can be corrected for influences of external disturbance forces in the following manner. As described above, components of equivalent external disturbance forces are measured by sensors of the gravity gradiometer. Actuators such as actuator 610 or the transducer sensors 71, may be used to counteract the detected components of the equivalent external disturbance force. Such correction forces may only partially correct for the equivalent external forces or correction forces may not be applied. In this case the components of the external disturbance forces are calculated from the measured equivalent external disturbance forces. The output of the gravity gradiometer is then numerically corrected for the external disturbance force using the previously determined respective constants K_{ei}.

In one specific variation the gravity gradiometer may also be arranged so that the motion of the gravity gradiometer 1 is corrected for 6 degrees of freedom (rotation about three orthogonal axes and translation along three orthogonal axes).

Although the invention has been described with reference 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 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 variations from the described embodiment are possible.

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 documents WO 90/07131 and PCT/AU2006/001269 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 not to preclude the presence or addition of further features in various embodiments of the invention.

The Claims:

1. A method of detecting a change in gravity gradient using a gravity gradiometer, the gravity gradiometer comprising a detector for detecting the change in gravity gradient, the gravity gradiometer further comprising a sensor for generating a disturbance signal in response to an external disturbance, the method comprising the steps of:

exposing the gravity gradiometer to the external disturbance during operation of the gravity gradiometer;

detecting the disturbance signal;

receiving an output signal from the detector of the gravity gradiometer; and

numerically correcting the output signal for an impact that a component of the gravity gradiometer experiences as a consequence of the external disturbance using a response parameter that associates the external disturbance with a disturbance experienced by that component.

2. The method of claim 1 wherein the response parameter is dependent on a mechanical responsiveness of the component to the external disturbance.

3. The method of claim 1 or 2 wherein the gravity gradiometer comprises a support structure that supports the detector and that is arranged to attenuate an impact of the external disturbance on the detector and wherein the component is a part of the detector.

4. The method of any one of the preceding claims

comprising correcting the output signal by applying a correction force, the correction force being correlated with the external disturbance, wherein the correction force reduces an impact of the external disturbance and the output signal is then numerically corrected for at least a portion of a remaining impact of the external disturbance on the output signal.

5. The method of any one of the preceding claims comprising the steps of:

applying an external force to the gravity gradiometer;

detecting the external force;

analysing if the component of the gravity gradiometer experiences a force that is correlated with the external force; and, if the correlation has been identified; and

calculating the response parameter.

6. The method of claim 5 wherein the component includes the detector of the gravity gradiometer and the step of analysing if the component of the gravity gradiometer experiences a force that is correlated with the external force comprises receiving a detector signal that includes the gravity gradient signal and analysing if that signal is correlated with the detected external force.

7. The method of any one of claims 1 to 4 comprising calculating the response parameter numerically using a mathematical model that represents a mechanical responsiveness of the component.

8. The method of any one of the preceding claims wherein the sensor for generating a disturbance signal is one of a plurality of sensors for generating disturbance signals and wherein the method comprises detecting a plurality of the disturbance signals in response to the external disturbance and wherein each sensor is arranged to detect at least one of: a force associated with a rotation about one of three orthogonal axes and a force associated with a motion along one of three orthogonal axes.

9. The method of any one of claims 1 to 7 wherein the disturbance is an electromagnetic disturbance and the sensor for generating a disturbance signal generates a signal in response to the electromagnetic disturbance.

10. The method of any one of the preceding claims wherein the method is operated by a feed-forward control arrangement for reducing transmission of the external disturbance to the component of the gravity gradiometer.

11. The method of any one of the preceding claims wherein the gravity gradiometer comprises a support structure and a pivot that couples the detector including the component to the support structure and wherein the response parameter is dependent on an equivalent spring constant of the pivot.

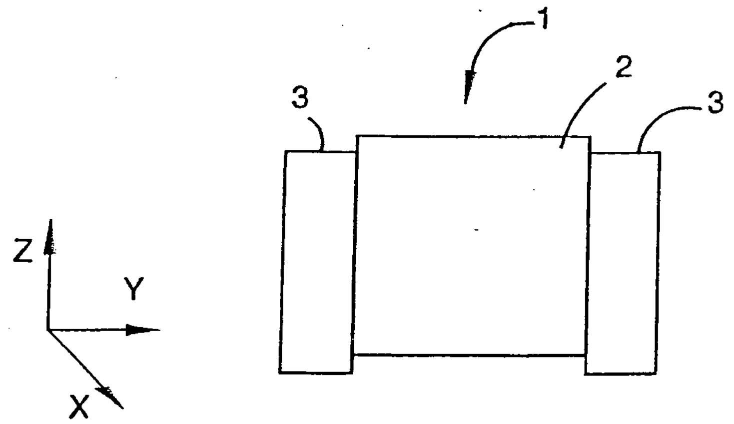


FIGURE 1

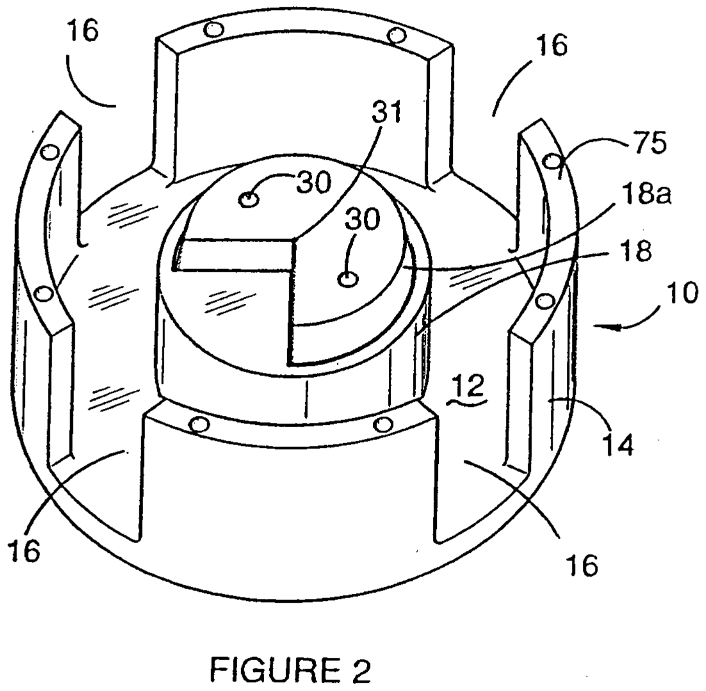


FIGURE 2

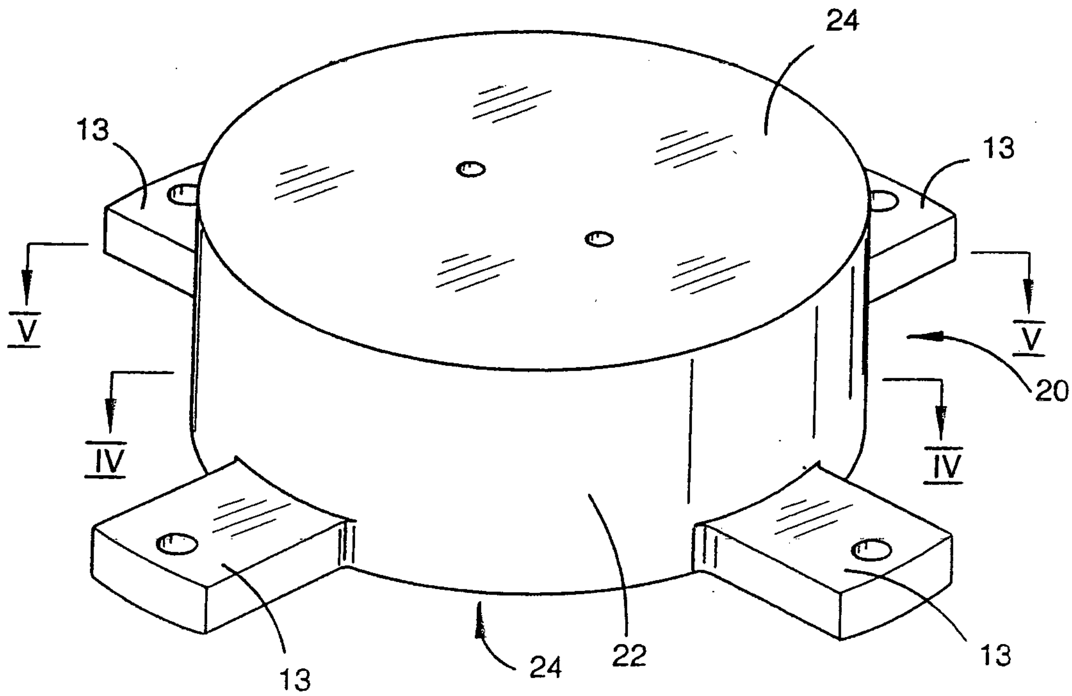


FIGURE 3

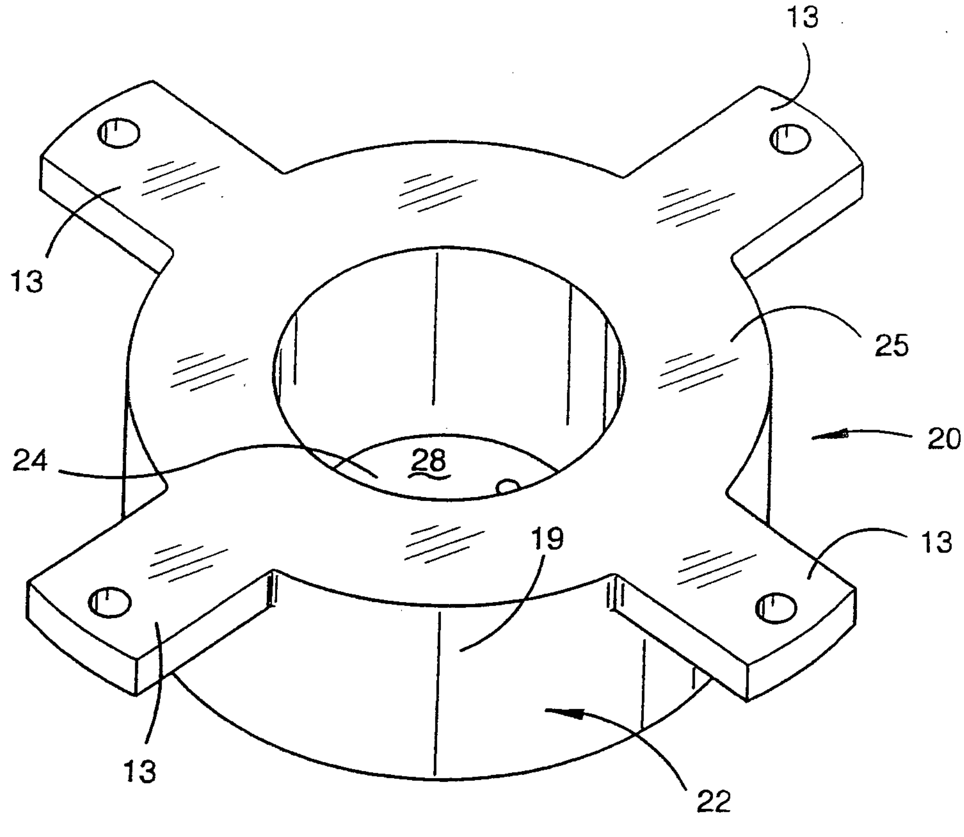


FIGURE 4

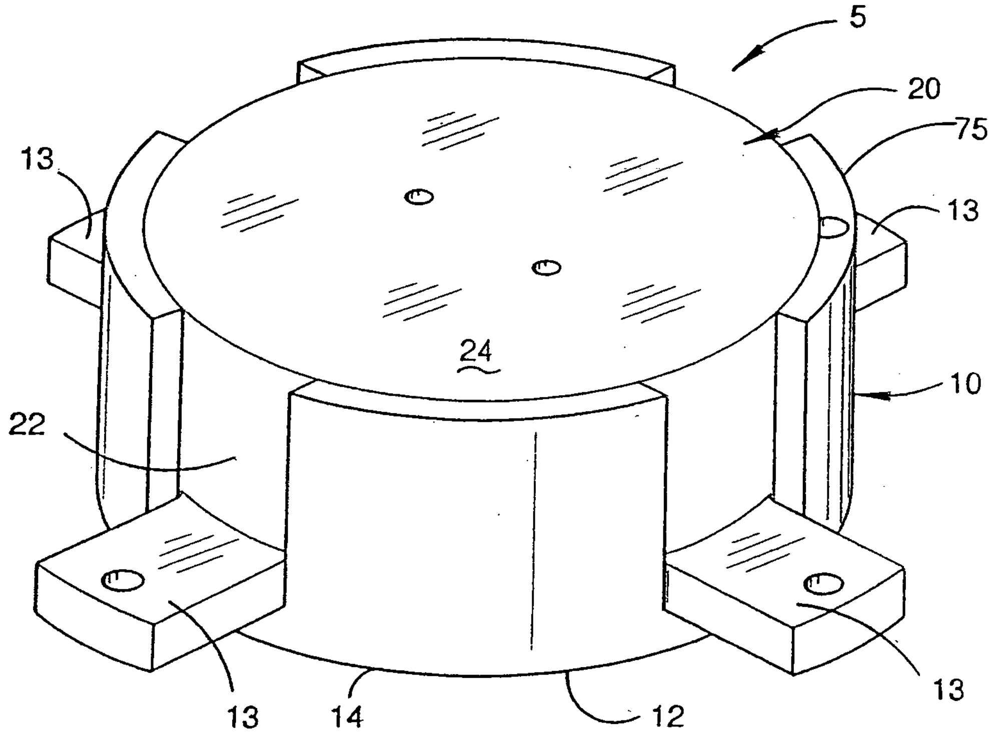


FIGURE 5

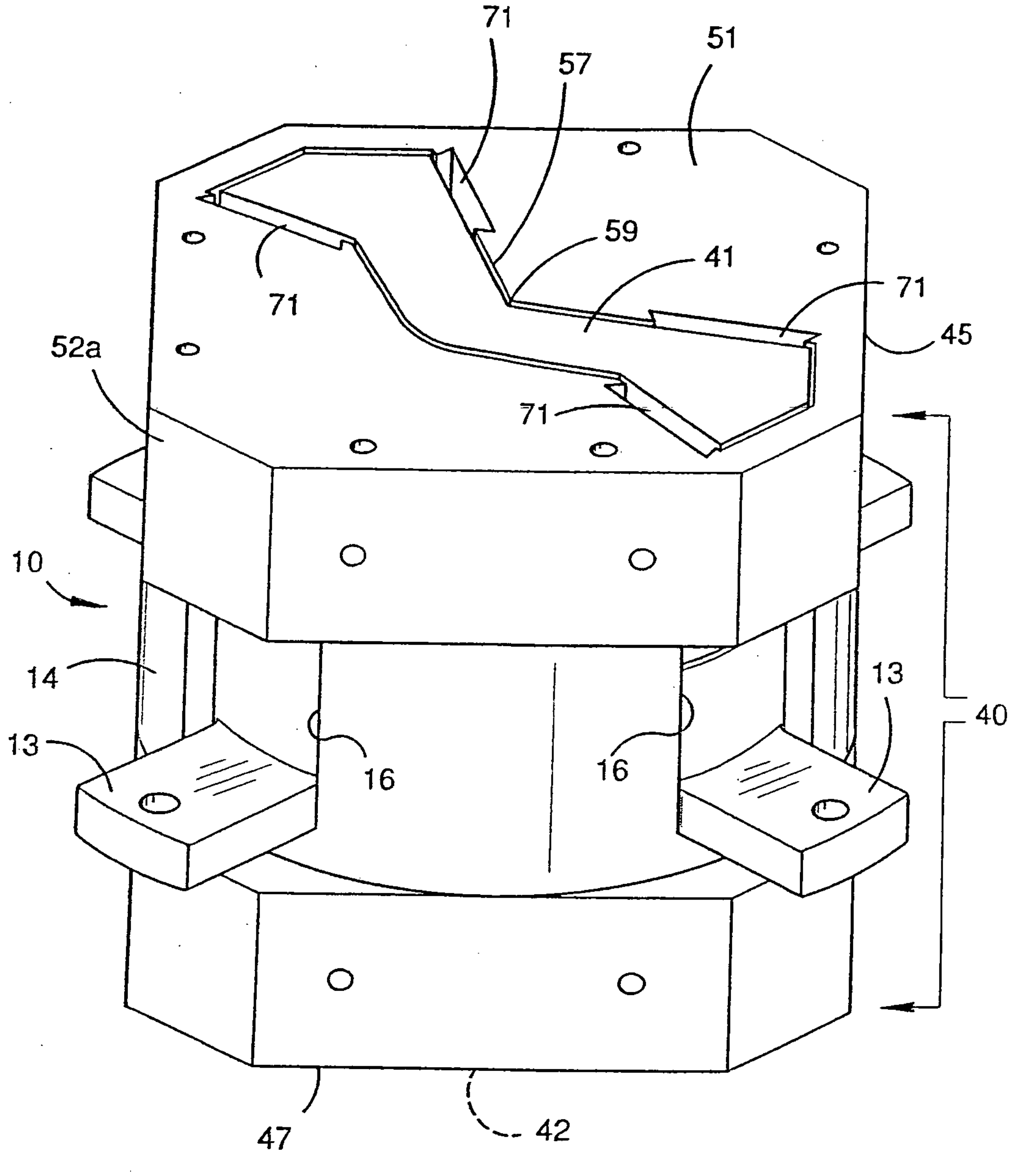


FIGURE 6

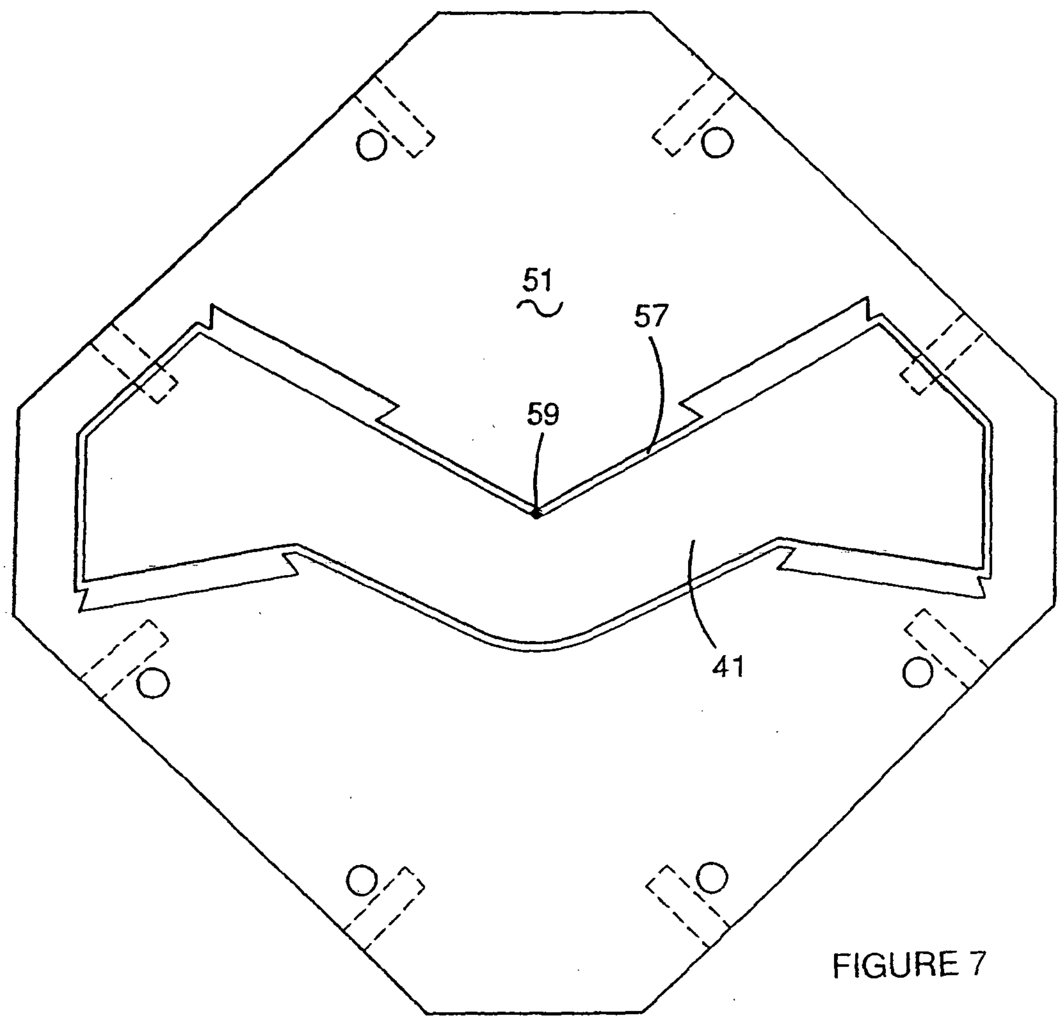


FIGURE 7

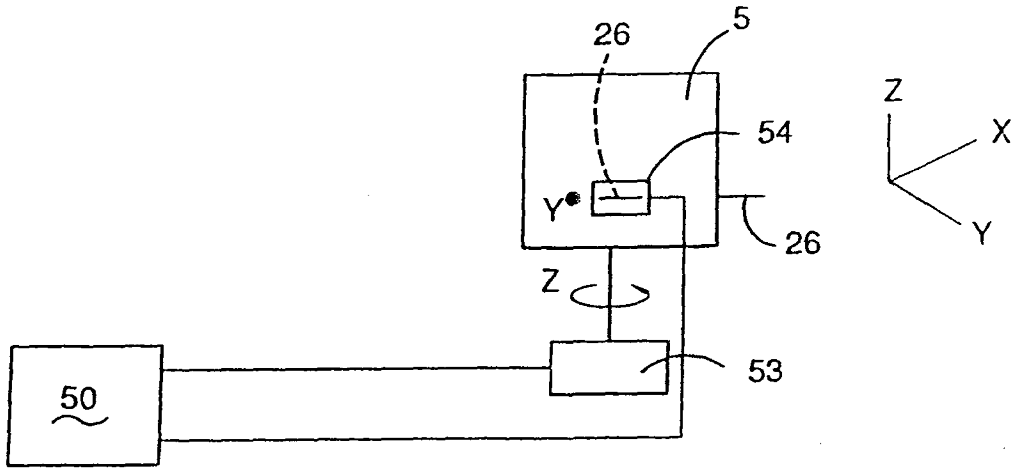


FIGURE 8

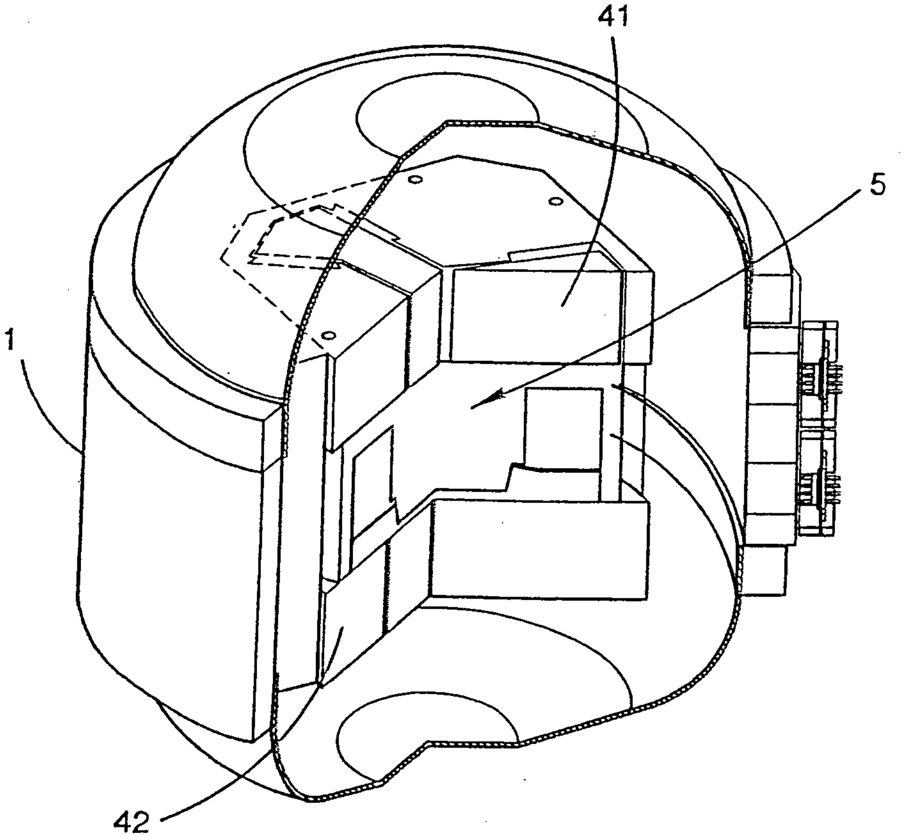
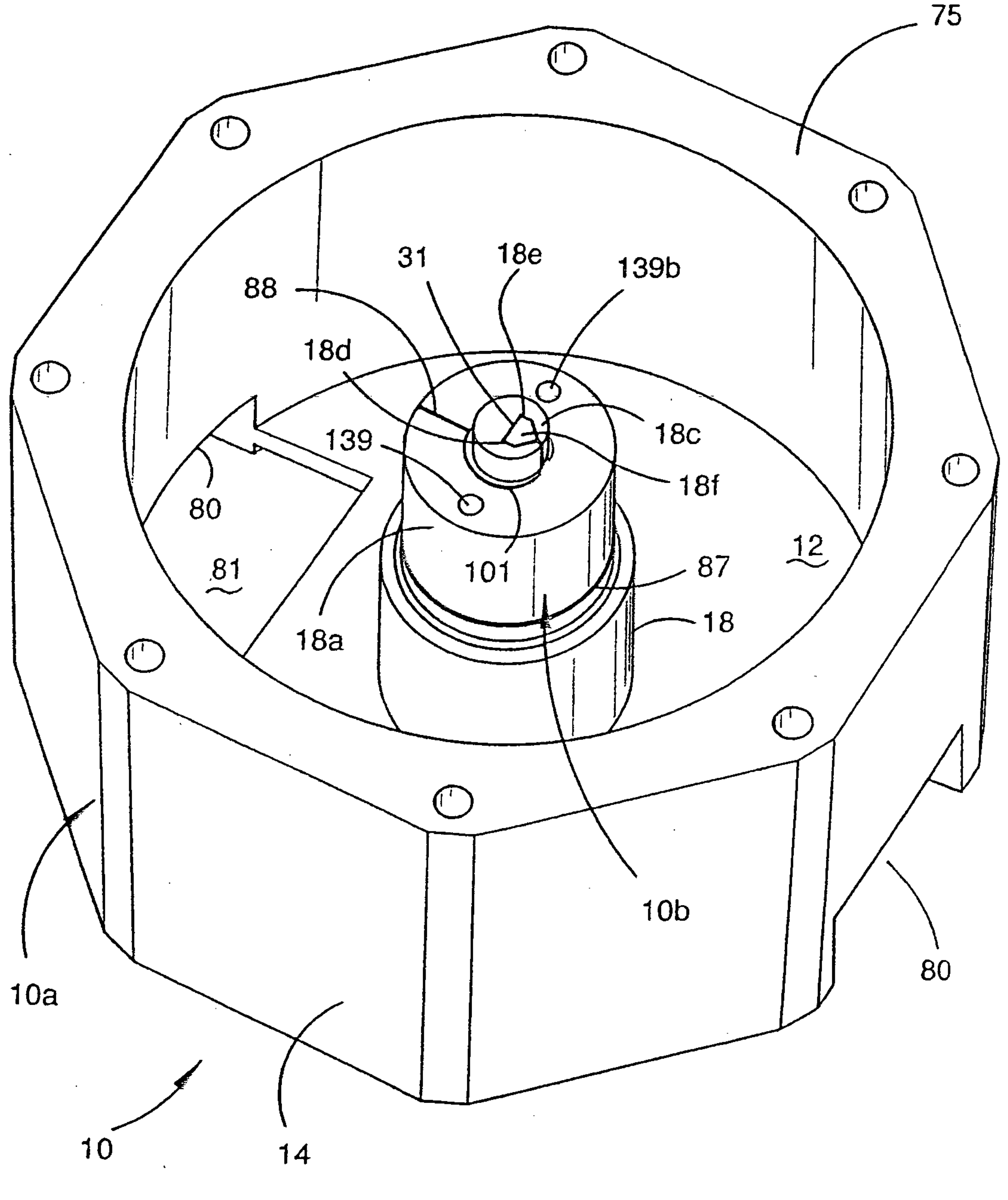


FIGURE 9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31
18e
139b
88
18d
18c
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18f
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12
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87
18a
18
10b
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14

FIGURE 10

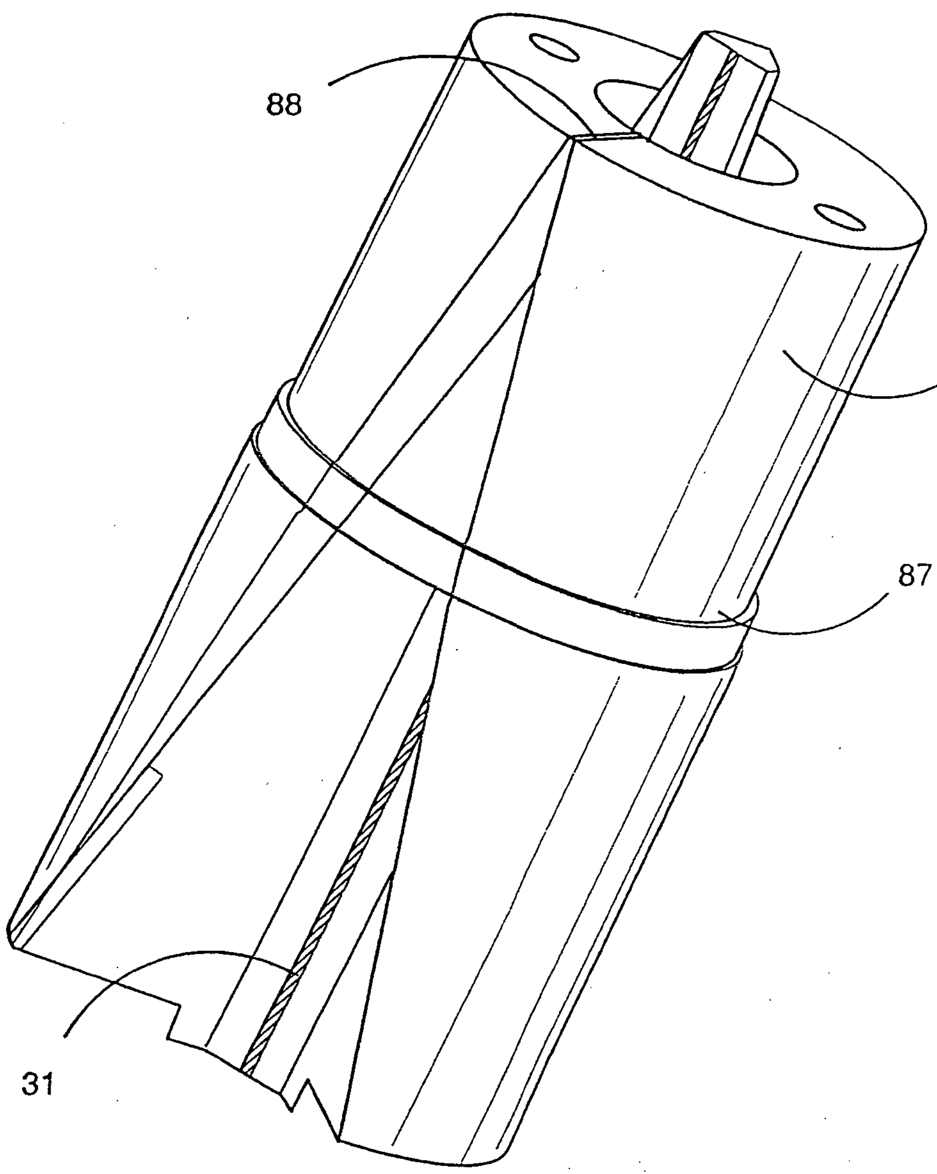


FIGURE 11

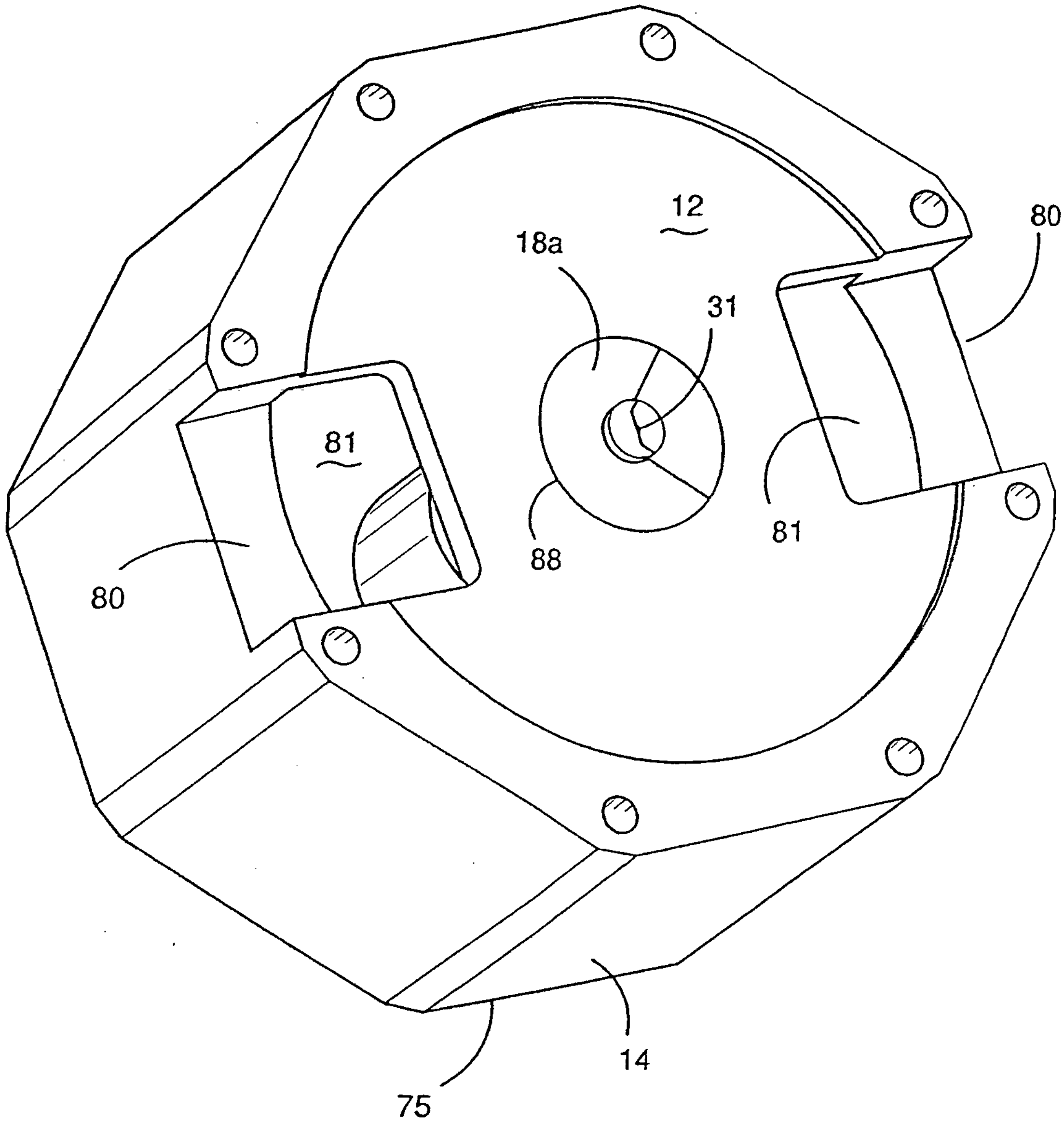


FIGURE 12

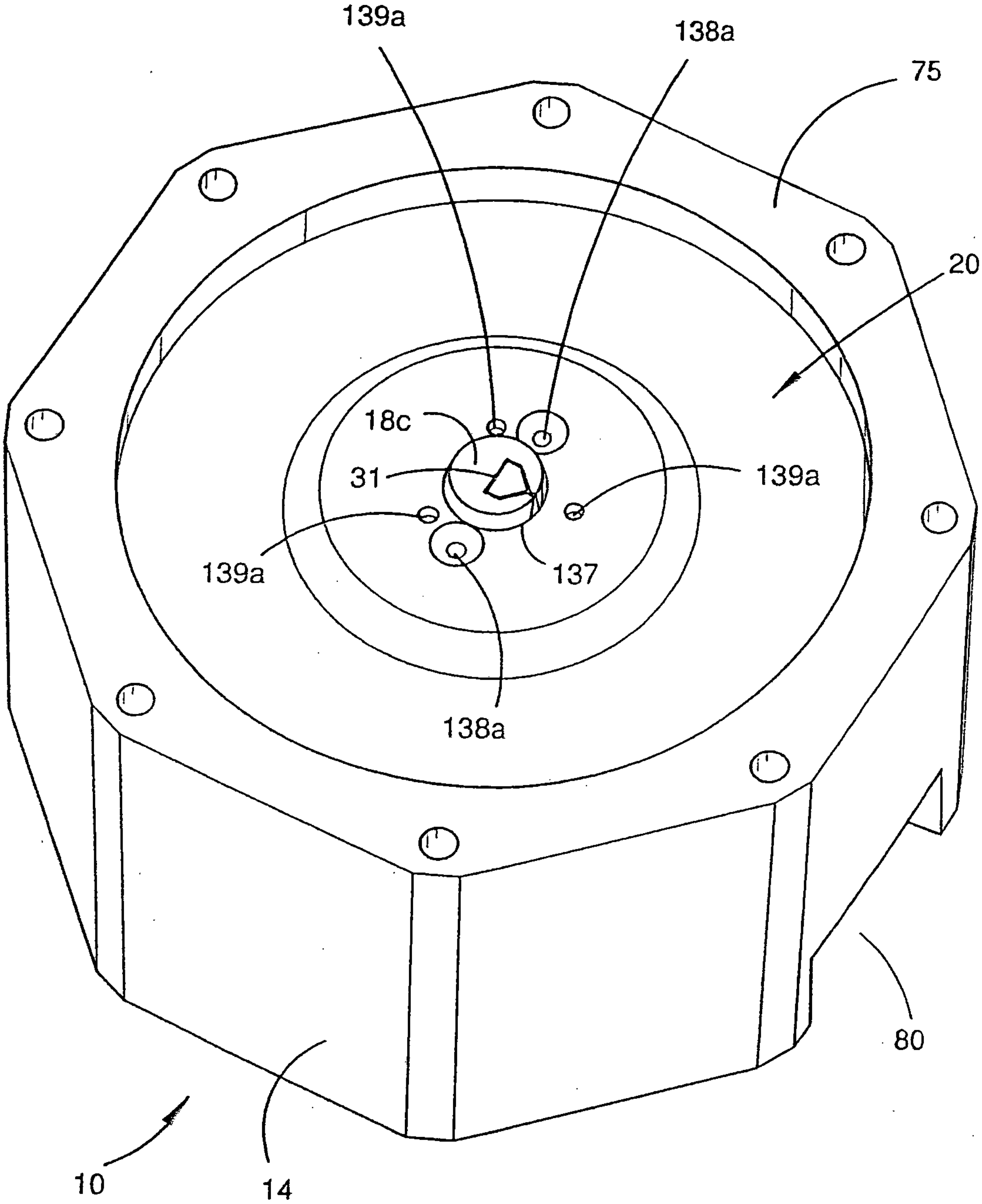


FIGURE 13

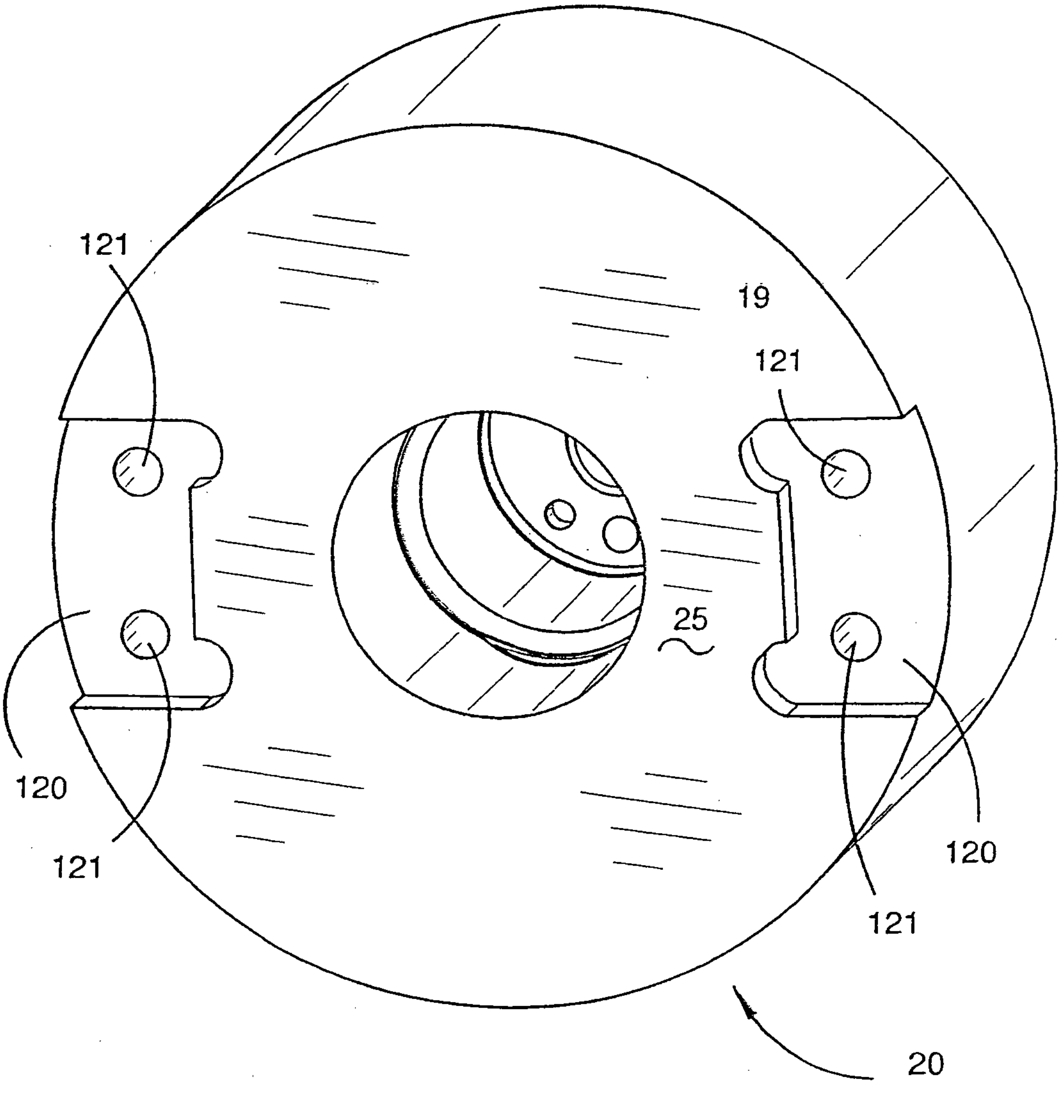


FIGURE 14

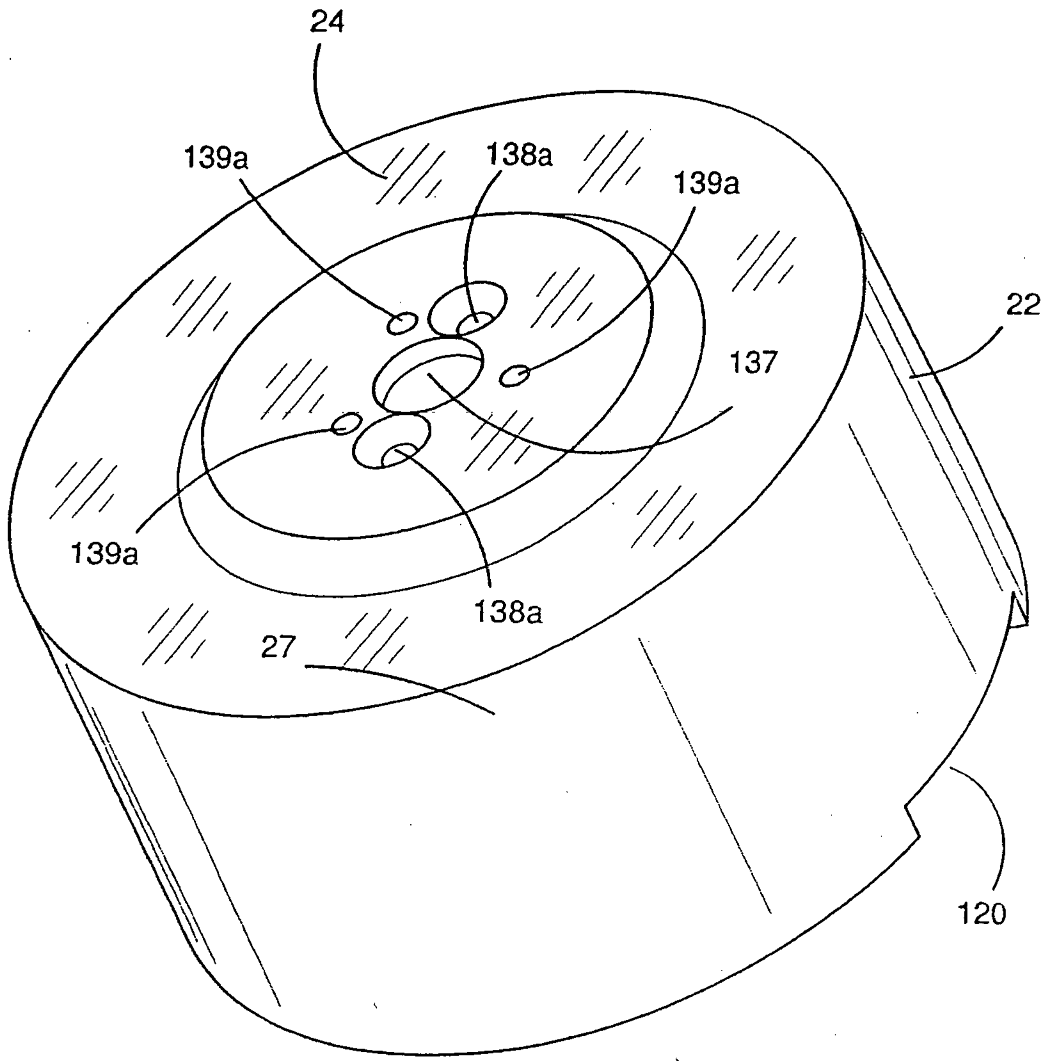


FIGURE 15

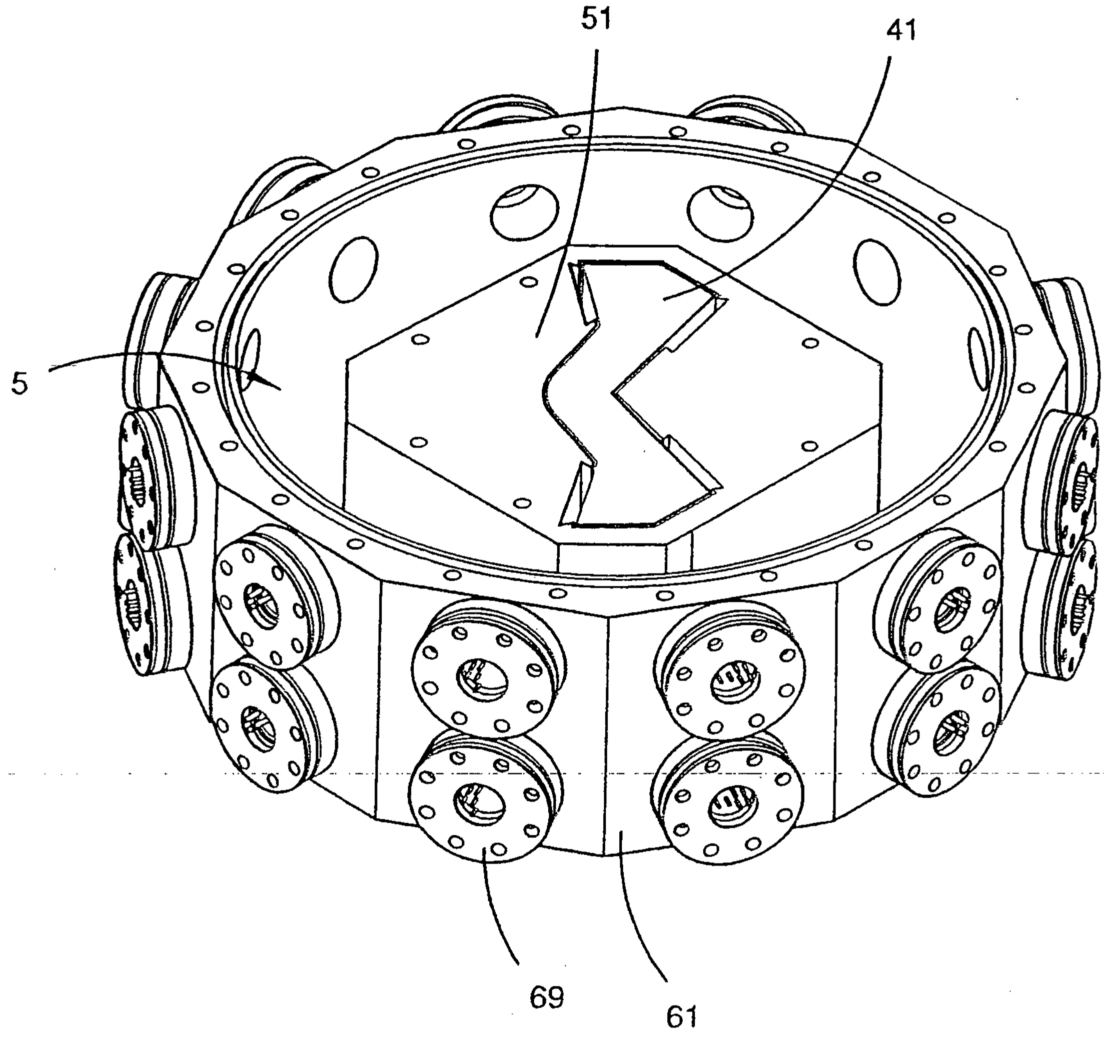
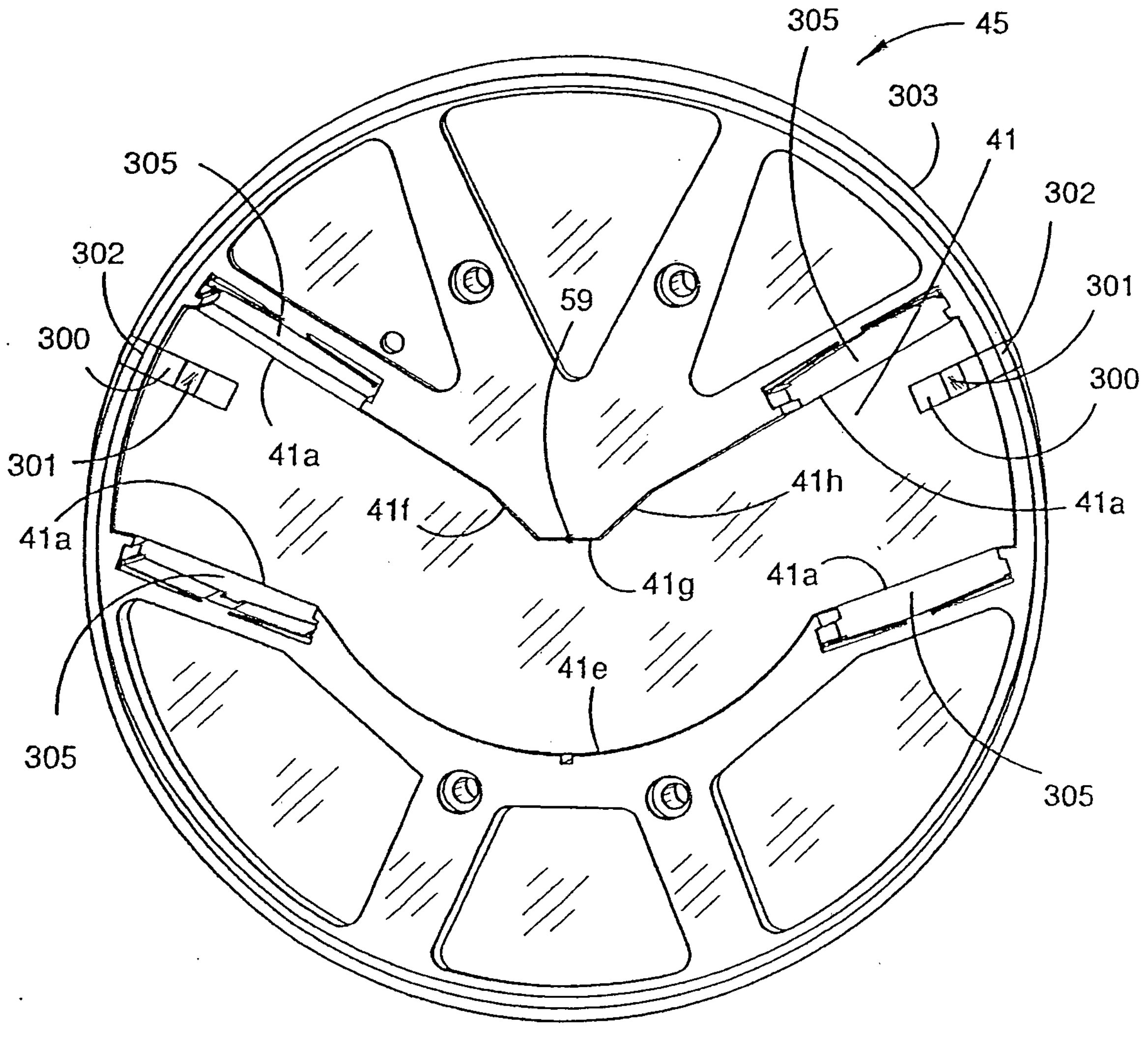


FIGURE 16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41e
305

FIGURE 17

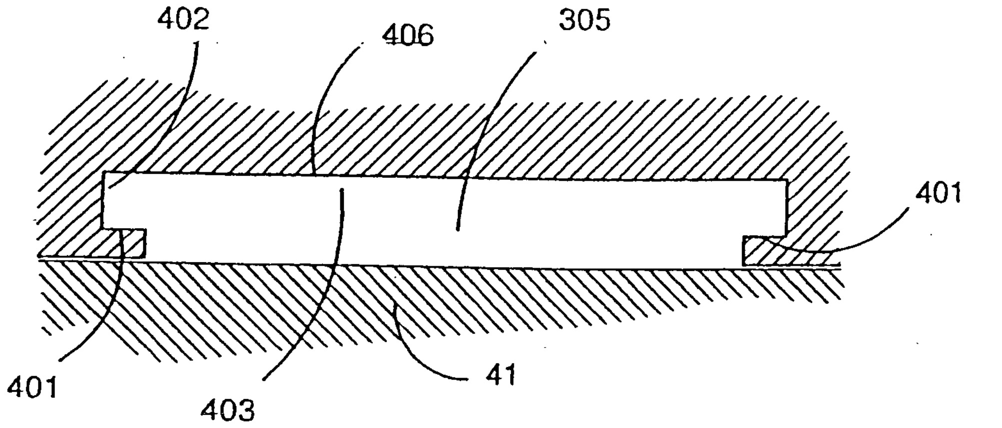


FIGURE 18

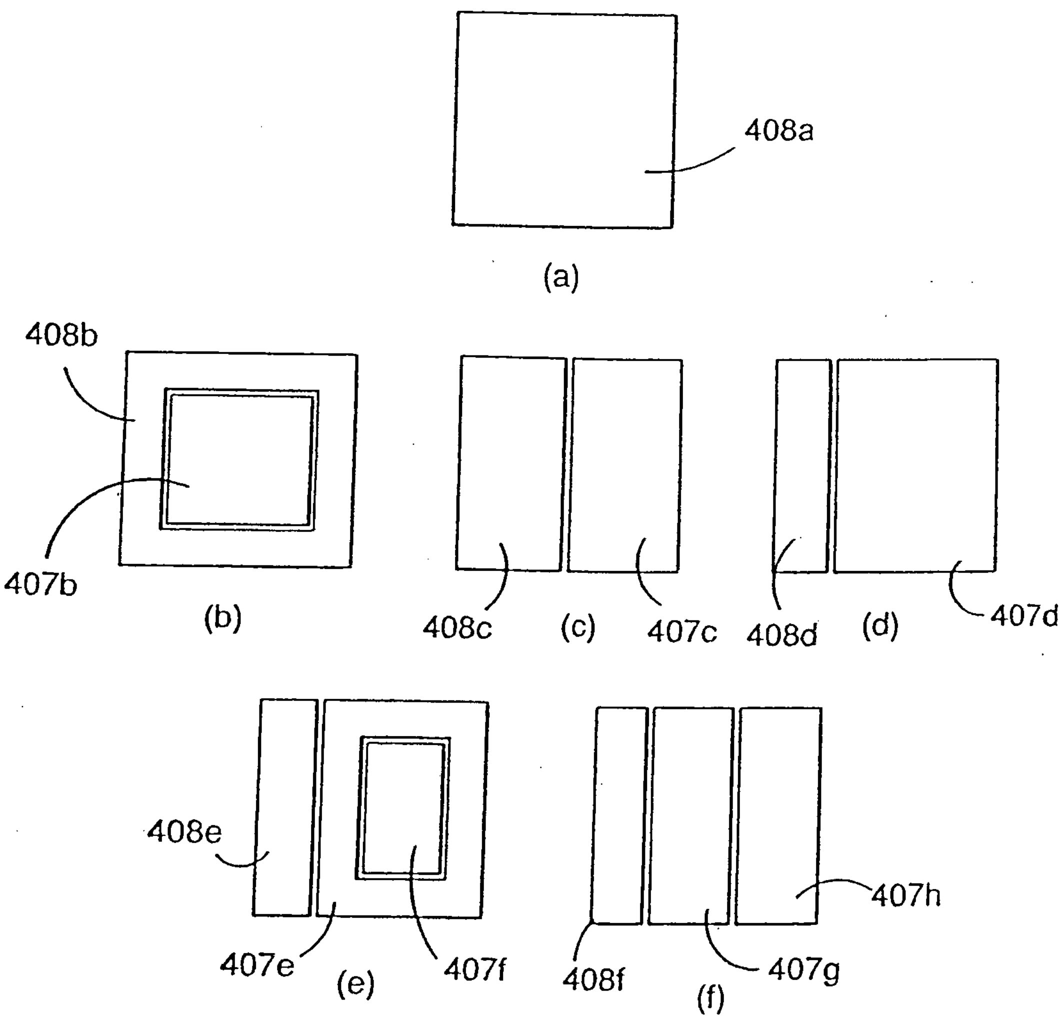


FIGURE 19

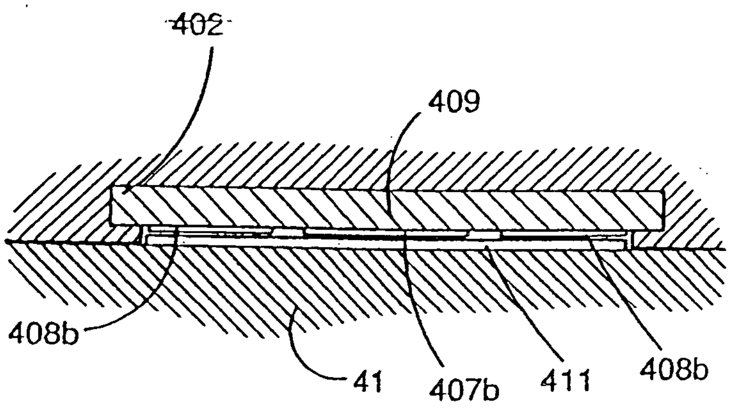


FIGURE 20

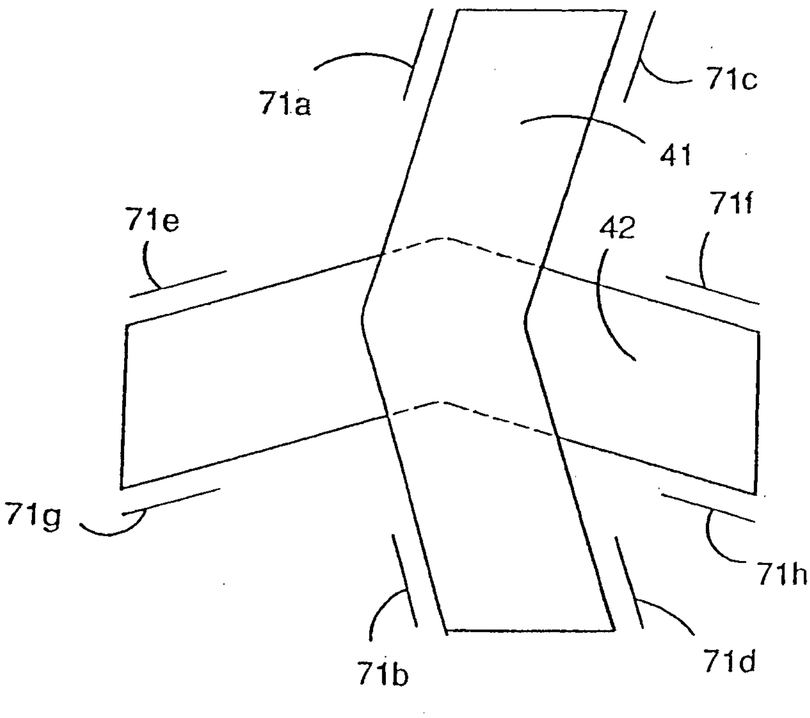
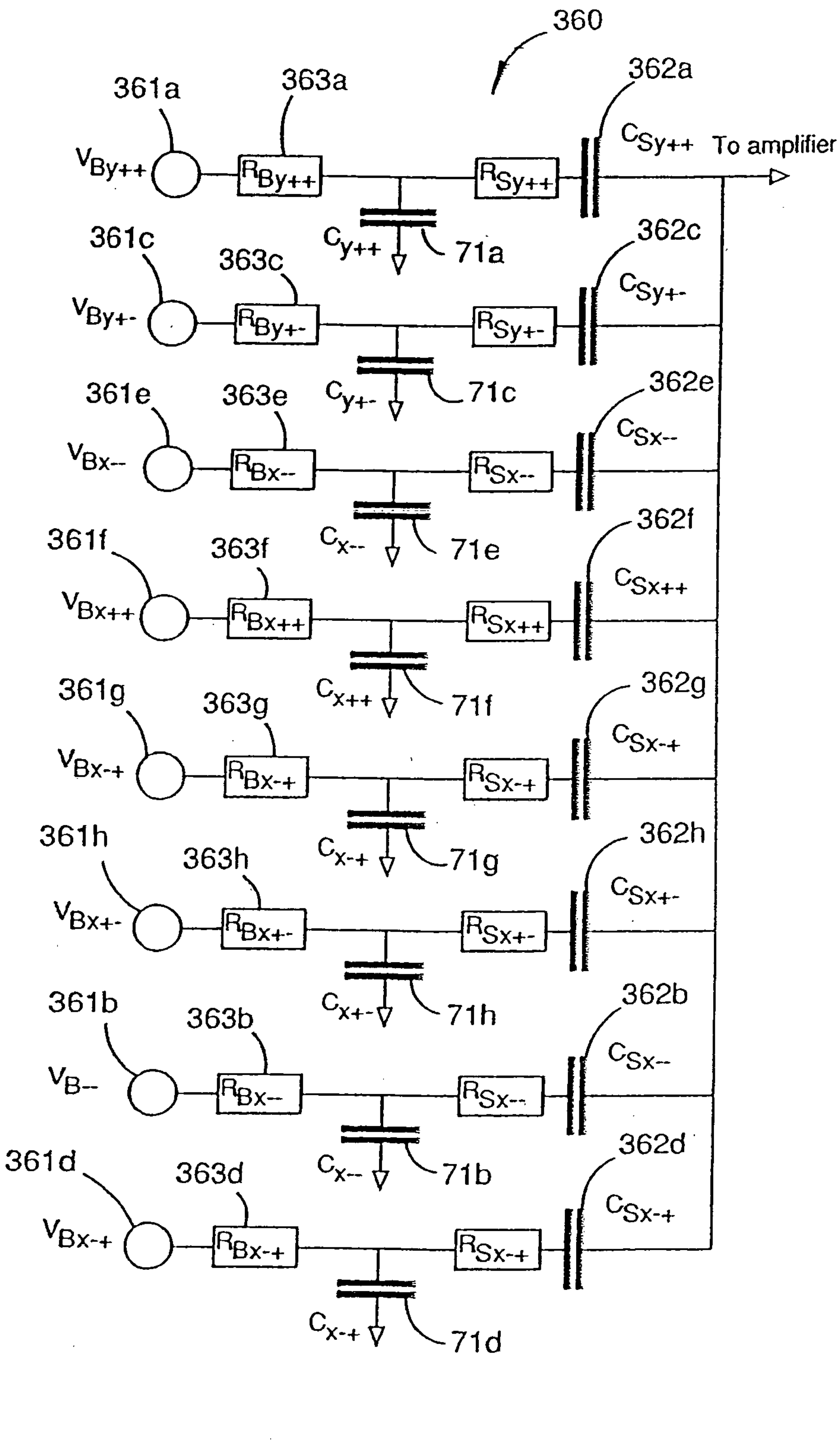


FIGURE 21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363a
362a
VBy++
RBy++
RSy++
CSy++
To amplifier
Cy++
71a
361c
363c
362c
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RBy+-
RSy+-
CSy+-
Cy+-
71c
361e
363e
362e
VBx--
RBx--
RSx--
CSx--
Cx--
71e
361f
363f
362f
VBx++
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FIGURE 22

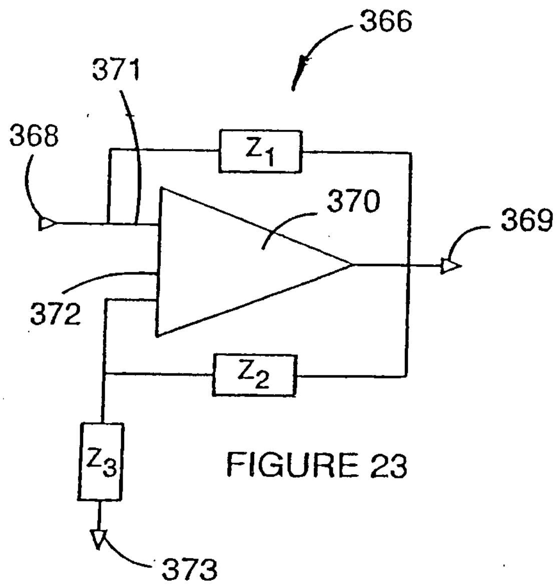

FIGURE 23

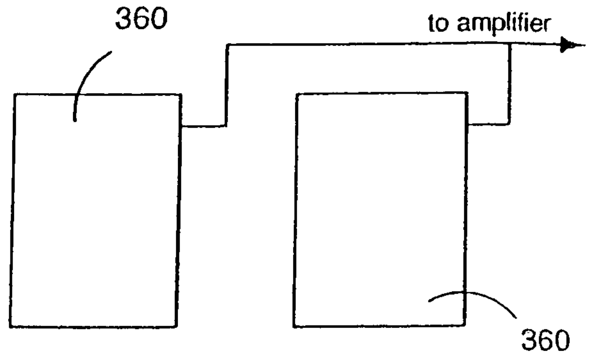

FIGURE 24

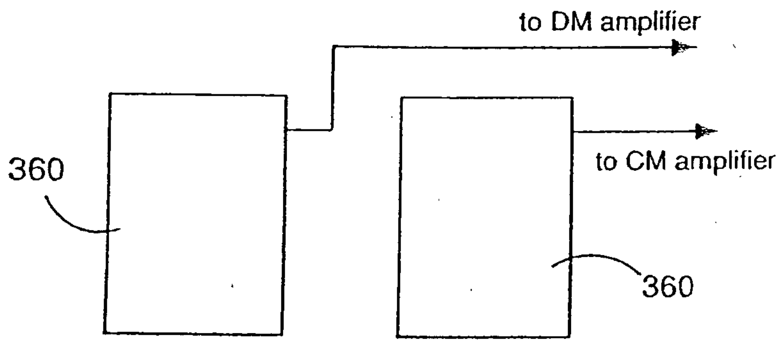

FIGURE 25

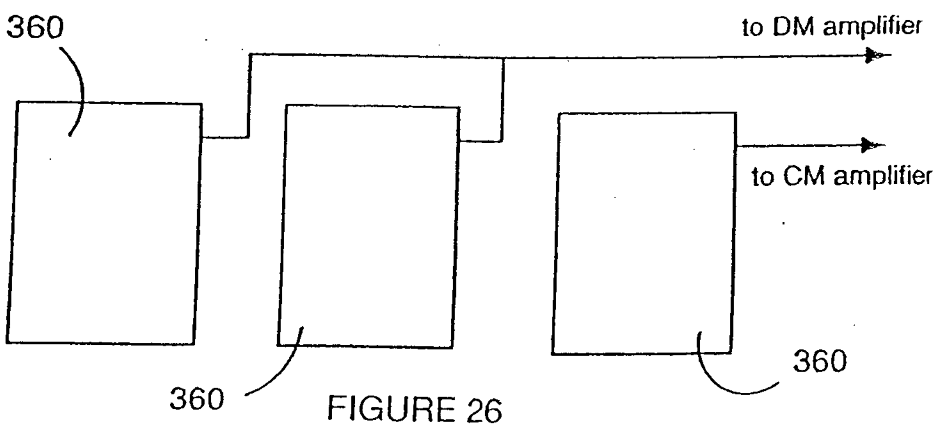

FIGURE 26

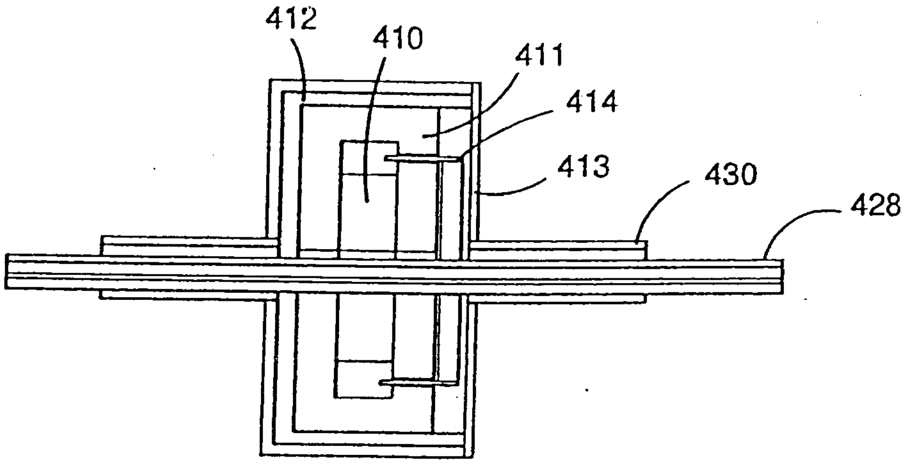

FIGURE 27

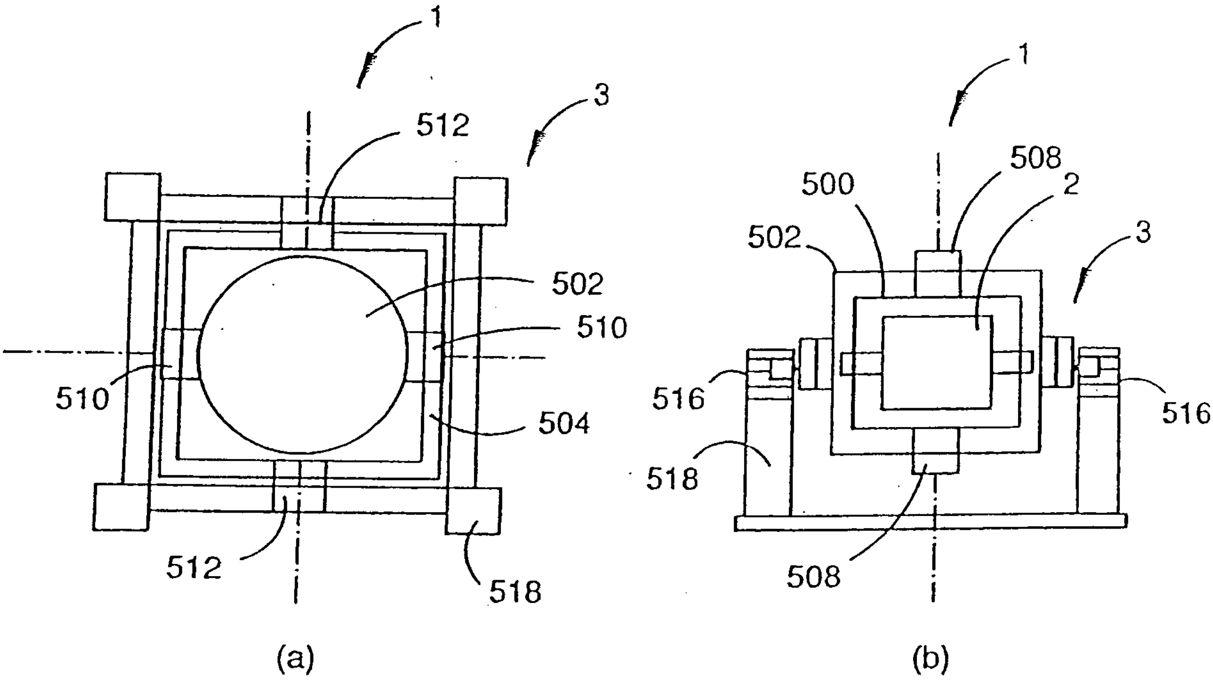

FIGURE 28

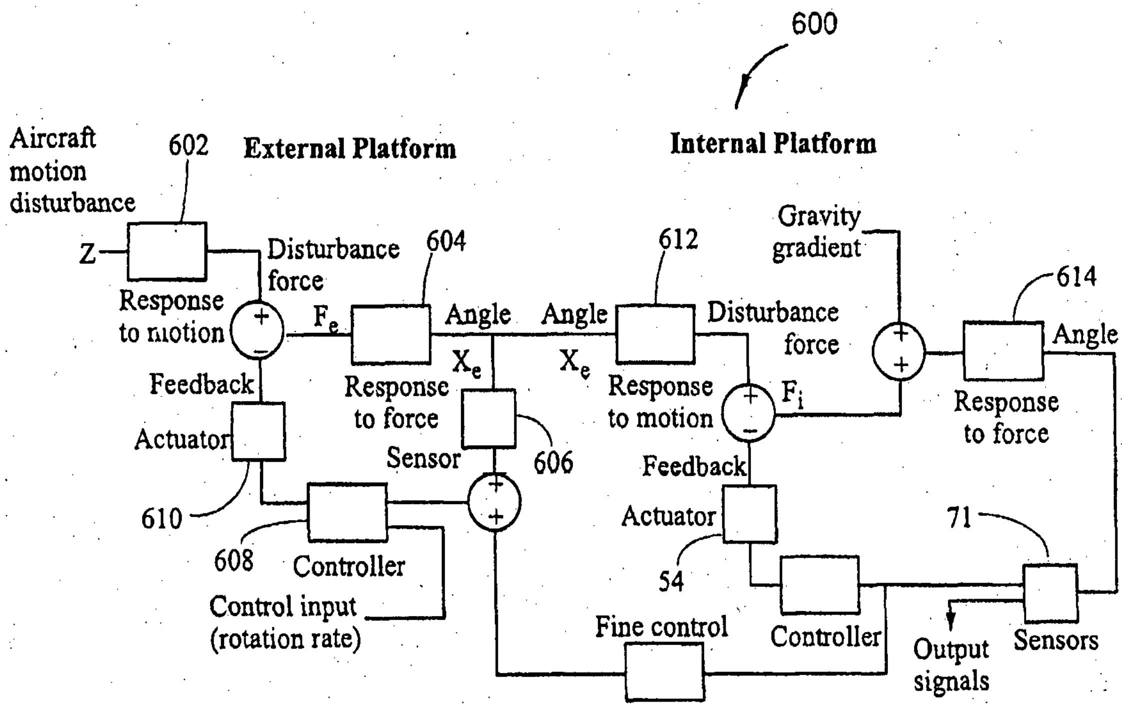

FIGURE 29

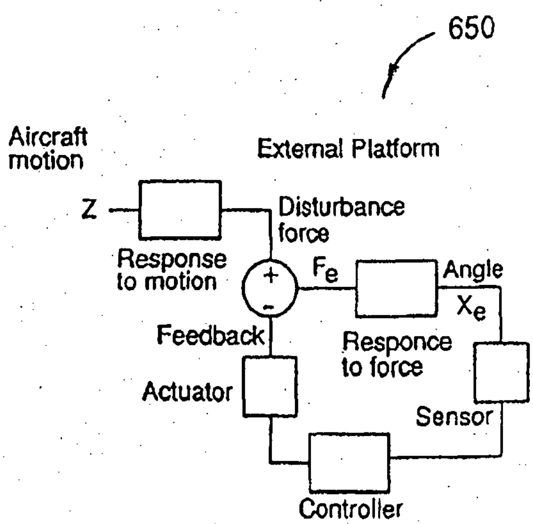

FIGURE 30

INTERNATIONAL SEARCH REPORT

International application No.
PCT/AU2011/000361

A. CLASSIFICATION OF SUBJECT MATTER Int. Cl. *G01V 7/16* (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; G01V7/IC; GRAVITY; GRADIENT, DERIVATIVE; GRADIOMETER; SPRING CONSTANT; AIRCRAFT, AEROPLANE, AIRBORN, HELICOPTER; MOVEMENT, ACCELERATE, TURBULENCE, DECELERATE; CORRECT, COMPENSATE, FEED FORWARD, ELIMINATE; FORCE, IMPACT, DISTURBANCE; EXTERNAL, UNWANTED, SPURIOUS, ADDITIONAL and similar keywords	

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2008/0115376 A1 (VAN KANN) 22 May 2008 Figures 29-30; paragraphs [0057], [0063], [0122-0123], [0125-0134]	1-2, 4-8, 10-11
X	US 2002/0092350 A1 (ETKIN et al.) 18 July 2002 Abstract, Figures 1A, 5E and 4, paragraphs [0019], [0073], [0077], [0085], [0091], [0101-0103], [0106-107], [0115], [0126-0127], [0140-0142], [0158] and entire page 1	1-11

☐ Further documents are listed in the continuation of Box C ☒ See patent family annex

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

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Date of the actual completion of the international search 27 June 2011	Date of mailing of the international search report 04 JUL 2011
Name and mailing address of the ISA/AU AUSTRALIAN PATENT OFFICE PO BOX 200, WODEN ACT 2606, AUSTRALIA E-mail address: pct@ipaustralia.gov.au Facsimile No. +61 2 6283 7999	Authorized officer **EVA DE KOOL** AUSTRALIAN PATENT OFFICE (ISO 9001 Quality Certified Service) Telephone No : +61 2 6283 2477

INTERNATIONAL SEARCH REPORT Information on patent family members	International application No. **PCT/AU2011/000361**

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					
US	2008115376	AR	062968	AU	2007249127	CA	2690933
		CL	27952007	PE	09682008	US	7559149
		WO	2008061275				
US	2002092350	AU	21398/02	CA	2429828	EP	1337879
		RU	2003119136	US	6837106	WO	0244757

Due to data integration issues this family listing may not include 10 digit Australian applications filed since May 2001.

END OF ANNEX