

April 15, 1969

P. L. CONTENSOU ET AL

3,438,267

MICRO-ACCELEROMETER

Filed March 28, 1966

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FIG. 1

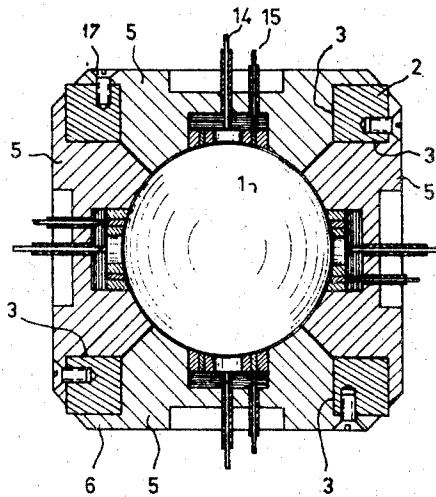
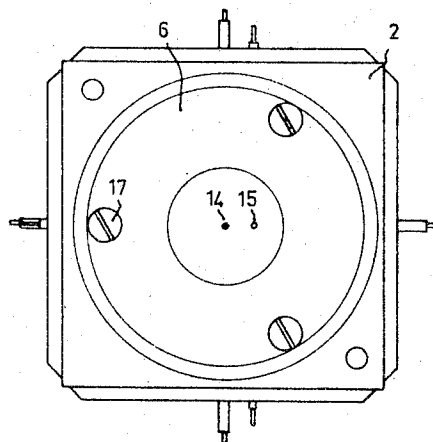


FIG. 3



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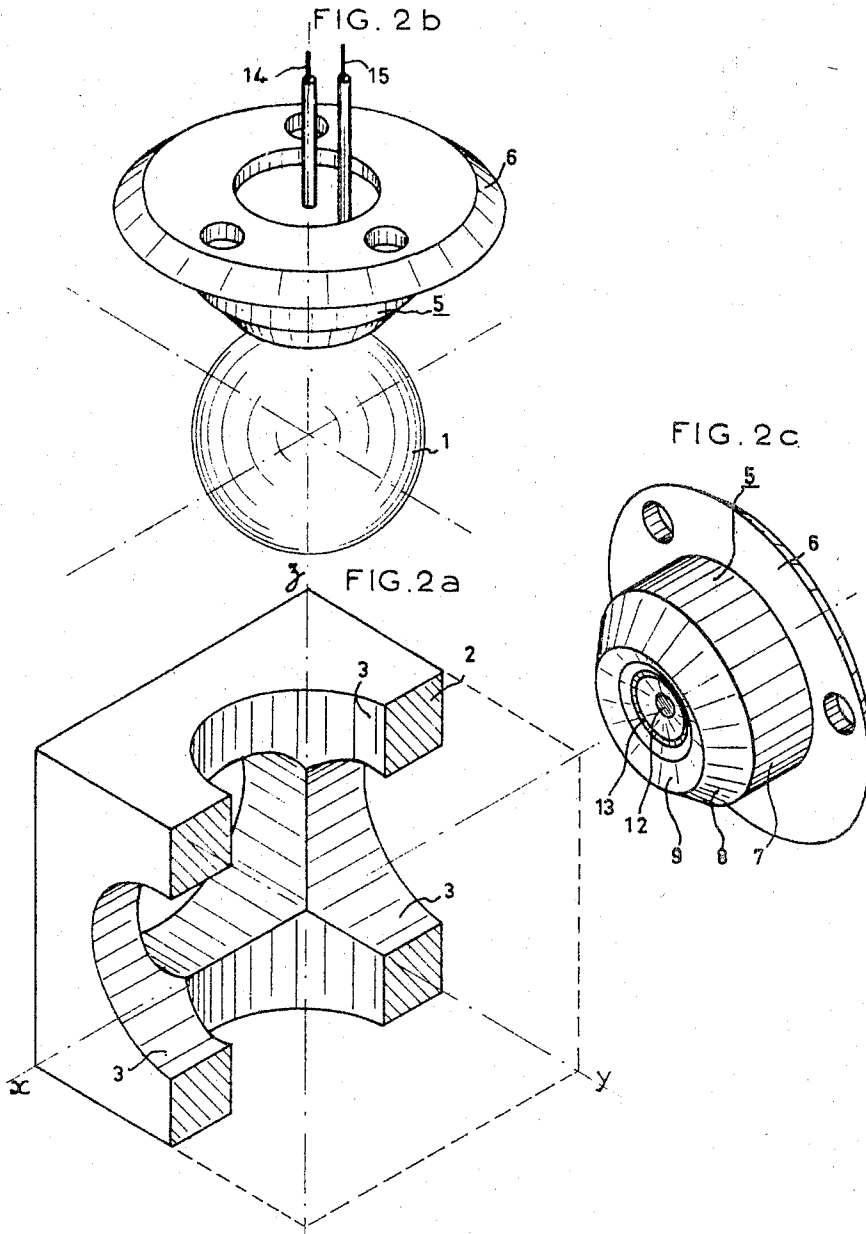
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FIG. 4

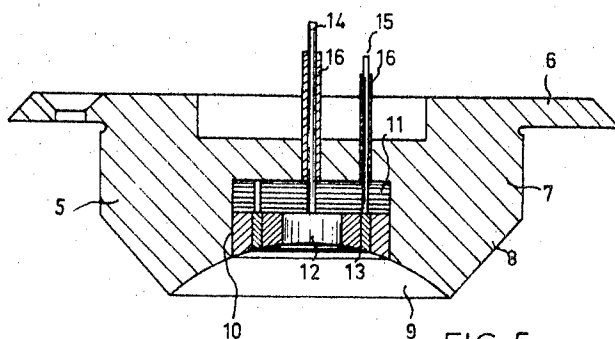


FIG. 5

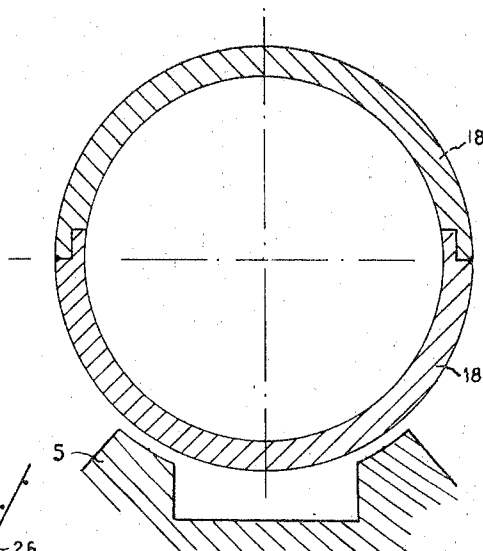
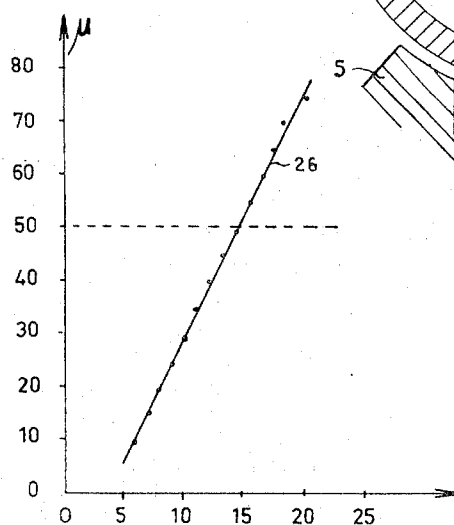


FIG. 7



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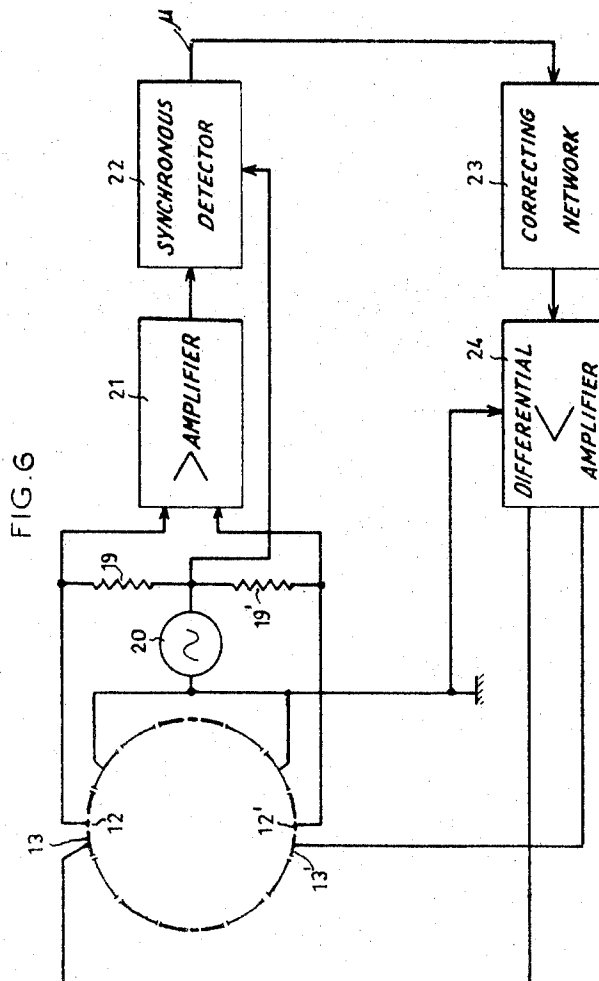
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FIG. 8

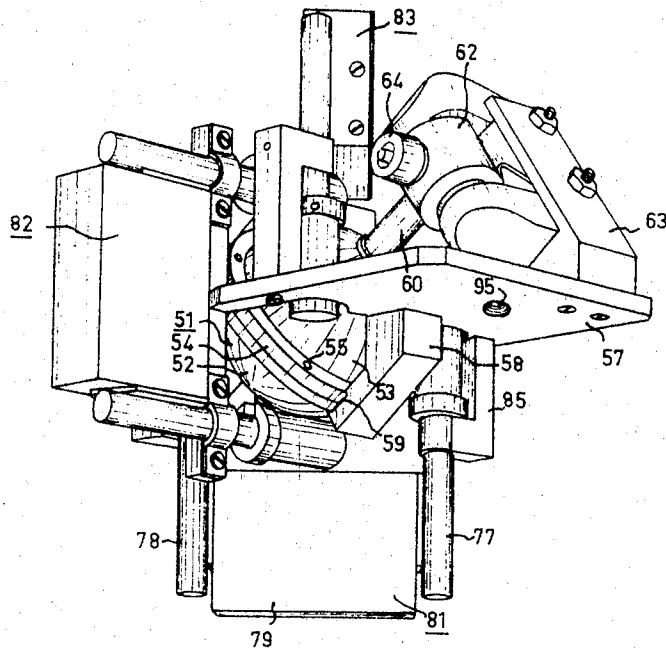
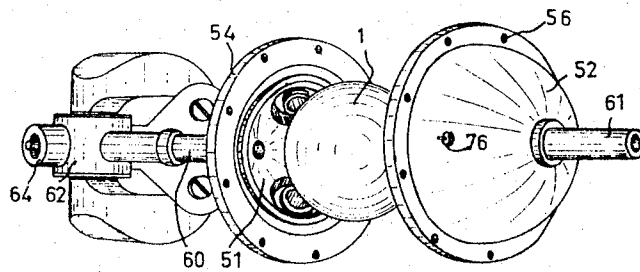


FIG. 9



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FIG. 10

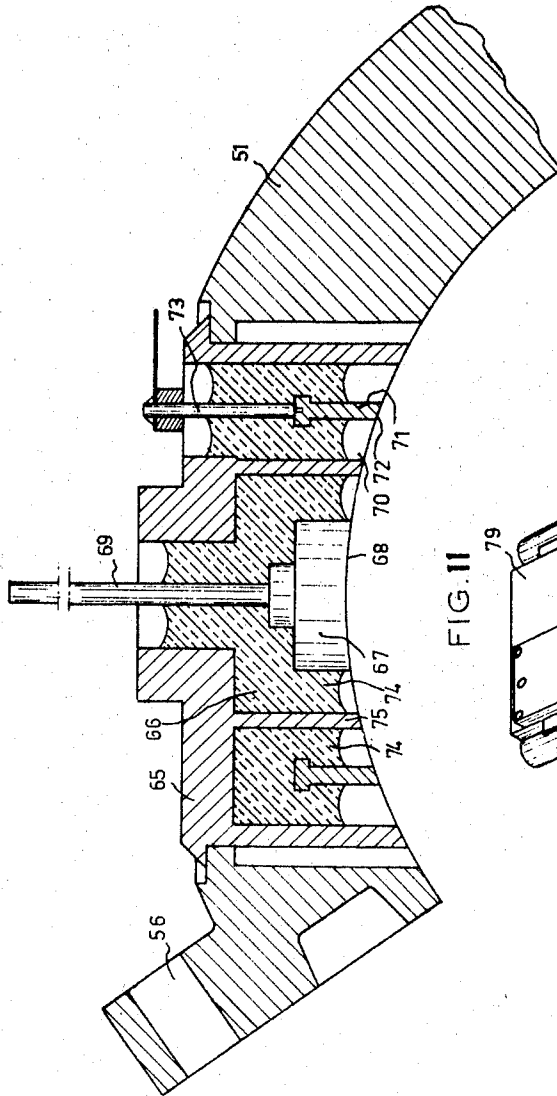
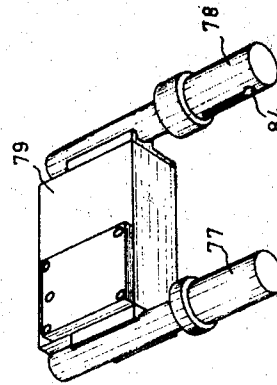


FIG. 11



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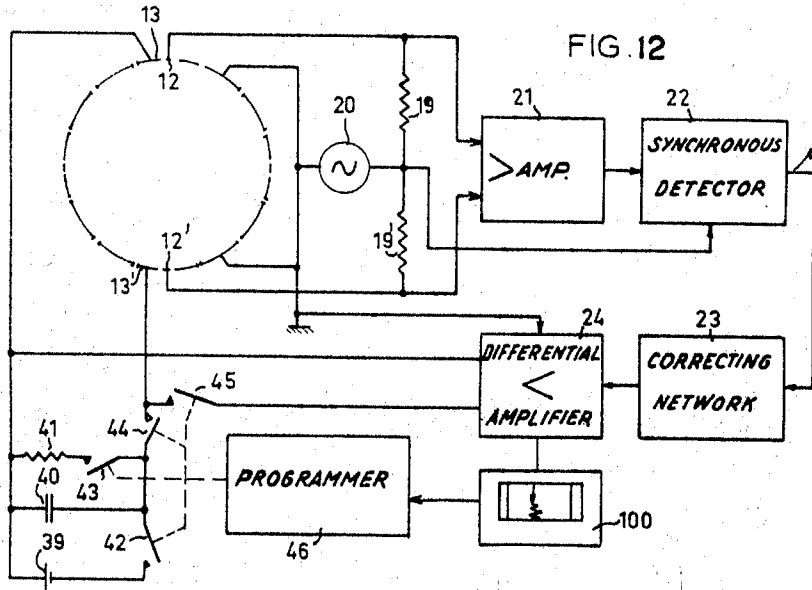
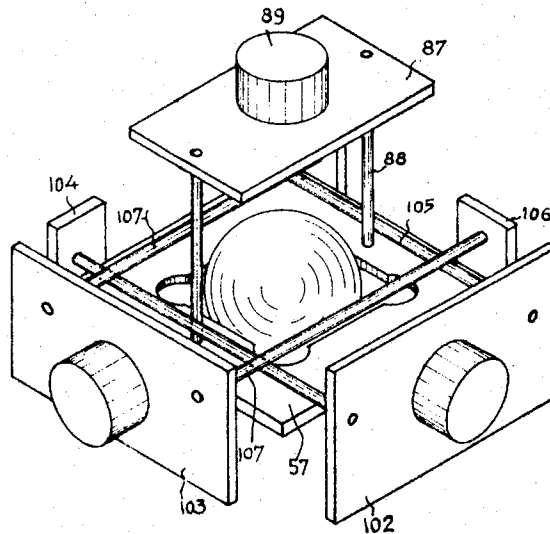


FIG. 15



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3,438,267

MICRO-ACCELEROMETER

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Claims priority, application France, Mar. 30, 1965,

11,246; Mar. 17, 1966, 53,929

Int. Cl. G01p 15/08

U.S. Cl. 73-517

8 Claims

ABSTRACT OF THE DISCLOSURE

A microaccelerometer of the electrostatic type providing an integrated acceleration measurement along 3 orthogonal axes comprising a hollow casing, a spherical sensor floating in the casing in a gravity-free condition when not subjected to acceleration, a plurality of opposed polar electrodes isolated from the casing in orthogonal relation thereto corresponding to the orthogonal axes, the polar electrodes forming capacitors by virtue of the connection with the spherical mass of the casing, and means for applying AC current between the casing and electrodes with receiving means for the output signals from the capacitors, the detected and amplified output signals indicating the displacement of mass of the casing from the orthogonal axes lying between the circumpolar electrodes to the capacitors.

This invention relates to a micro-accelerometer of ball type and, specially, a high sensitivity, three-dimensional micro-accelerometer of this type.

The object of the invention is to provide very high accuracy micro-accelerometers capable of measuring accelerations of the order of 10^{-8} to 10^{-9} g such as those accelerations applied by solar radiation pressure on satellites.

Ball accelerometers generally consist of a ball and a casing, means for sensing the position of the ball in the casing and means for controlling the position of the ball, these position controlling means being controlled by the position sensing means. Ball accelerometers in which the sensing means are of electrostatic or optical or magnetic type and in which the position controlling means are either magnetic or hydraulic have already been proposed. In the case of the previously indicated sensitivities, it is not possible to use balls made out of a magnetic material which react to the earth's magnetic field. Furthermore, it is not possible to link the ball to the casing by a flexible connection wire so as to fix the potential and the latter must be completely free and floating in its casing.

Another object of the invention is to provide a micro-accelerometer in which the ball position sensing means and the ball position controlling means are both electrostatic.

Generally speaking, the micro-accelerometer concerned by the invention consists of a floating spherical ball, that is to say, a ball which is not suspended and not linked to a wire, three electrostatic differential position sensors located round the ball and in its immediate vicinity and arranged to transmit signals representing the

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movements of the ball along three orthogonal axes with the center of the ball at the origin when the latter occupies a particular position termed "a balanced or at rest position," three ball positioning electro-static circuits located round the latter and in its immediate vicinity and arranged so as to produce mechanical action of the ball along the said three orthogonal axes, means for separately amplifying each of the signals transmitted by the position sensors and means for applying these to the positioning circuits whilst acting in the same direction as that of the position sensor transmitting the signal.

The position sensors and the position control devices are electrostatic or capacitive, that is to say consisting of capacitors the first electrode of which is the ball itself (which, of course, is a conductor) with the second electrode installed on the casing of the apparatus. The casing is substantially spherical and the diameters of the casing and the ball differ to a very slight extent. Electrodes insulated from the remainder of the casing are inserted in the spherical casing. There are twelve electrodes six of which, shaped in the form of spherical caps, are located around the poles where the three orthogonal axes whose origin is at the center of the spherical casing meet said casing with the six other electrodes consisting of spherical rings or segments surrounding the spherical caps and insulated from the latter. The pole electrodes are ball position sensing electrodes and the circumpolar electrodes are ball position control electrodes. The pole electrodes are supplied with alternating current and form, together with the conducting ball when the latter moves under the effect of acceleration forces, a variable capacitor with a capacitance depending on the position of the ball. Since the ball is free in the casing, its potential is fixed capacitatively through a capacitor which is formed by its own surface and the surface of the casing not occupied by the polar and circumpolar electrodes (the latter surface being taken as a potential reference surface), this capacitor being relatively large, and, as a result, having relatively low impedance. The signals received between two given and diametrically opposite polar electrodes are amplified and applied in the same suitable direction between the two circumpolar electrodes associated with said two given polar electrodes. A three component ball position follower system is thus formed with the signals applied to the three pairs of circumpolar electrodes respectively measuring the acceleration components applied to the ball.

As has just been explained, the fixed electrodes on the casing are portions of a spherical surface, cap (spherical segment with a base) or ring (spherical segment with two bases). The capacitances which are thus obtained are, for small values of the radius of the base of the cap or of the radius of the large base of the ring, larger than the capacitance which would be obtained between the ball and a flat electrode even in the case where this flat electrode would be infinite.

If R is the radius of the ball e the spacing between the concentric ball and casing, h the height of the cap and r the radius of the base of the spherical cap, the capacity between the sphere and the said spherical cap is

$$c_1 = 2\pi\epsilon_0 \frac{R}{e} h = 2\pi\epsilon_0 \frac{R}{e} [R - \sqrt{R^2 - r^2}] \quad (1)$$

where ϵ_0 is the permittivity of the vacuum or, more generally of the medium in the space existing between the casing and the ball.

The capacitance between the ball and an infinite plane at a distance of e' from the ball is (refer to C. Snow, "Formulas for Computing Capacitance and Inductance," National Bureau of Standards, Circular 544, Sept. 10, 1944):

$$C_2 = 2\epsilon_0 \sqrt{e'(e'+2R)} \sum_{s=1}^{\infty} \frac{1}{\sin h \frac{s\gamma}{2}}$$

$$\gamma = 2 \log \left[\frac{R + e' = \sqrt{e'(e'+2R)}}{R} \right]$$

For $R=20$ mm. and $e'=5.10^{-2}$ mm., Formula 2 gives $C_2=9$ pf. Assuming that $e+e'$, such a value of C_1 is obtained for $r=3.6$ mm.

It can thus be ascertained that, relatively to the ball, a cap with a base measuring a few millimeters can replace a large flat electrode.

The accelerometer concerned by the invention has a threshold sensitivity level of the order of $10^{-9} g$ and is designed to effect measurements of acceleration under conditions close to those of weightlessness and to be mounted on space vehicles.

Another object of this invention is to make the sensitivity of the micro-accelerometer vary as a function of the acceleration which it measures.

Another object of the invention is to provide means for calibrating the micro-accelerometer.

In a terrestrial laboratory, the micro-accelerometer is subjected to the gravitational field. It is, therefore, necessary that the measuring range of the micro-accelerometer be from g to $10^{-9} g$, that is to say 10^9 times the sensitivity threshold, that the stability of the response be 10^{-9} times the measuring range and that it be possible to subject the accelerometer to accurately definite accelerations having amplitudes which would lie between g and $10^{-9} g$. These three conditions are extremely difficult to fulfill in practice at the present stage of technical progress.

The calibration of the micro-accelerometer is effected by placing it in a free-falling capsule, preferably in a vacuum tube. A state of weightlessness is thus simulated and this simulation improves with the extent of the vacuum in the tube since the friction engendered by the remaining air on the capsule results in a deceleration which could reduce the accuracy of the simulation. In order to achieve a simulation of weightlessness of the order of $10^{-9} g$, a vacuum of the order of 10^{-5} mm. of mercury must be available. The duration of the simulation experiment depends on the height of the tube. The applicant has a vacuum column approximately 40 meters high thereby resulting in an experimental time of 2.8 seconds.

Calibration time is divided into two parts. Between initial instant t_0 and an instant t_1 , the accelerometer is placed in an operational state within its measuring range, that is to say, the ball, which is originally at rest in the casing, is led into the space in which it is subjected to the effect of the electrostatic positioning device. Between instant t_1 and the end of the calibration measurement time T , the accelerometer and the capsule which contains it is subjected to an acceleration of known amplitude compatible with the measuring range.

More specifically, at instant $(t_0 - \epsilon)$, preceding the instant of release, the accelerometer is subjected to an acceleration g and, at instant $(t_0 + \epsilon)$ immediately following the instant of release, it is subjected to a remaining acceleration of less than $10^{-9} g$. At instant $(t_0 - \epsilon)$, the ball shape is distorted under the effect of its own weight and is maintained in its position by the reaction of the casing. During time 2ϵ , this stress is freed and the ball gains ascending speed relative to the support. In order to effect calibration, it is necessary that the ball be led, in the time $(t_1 - t_0)$ which is only a fraction of the duration of free-fall $(T - t_0)$, within the measuring range

(range in which the follower system is operative) and that its residual kinetic energy be less than that which the follower forces can apply thereto and which correspond to the limits of the measuring range. This condition will be termed "the ball pre-positioning condition."

During the period $(T - t_1)$, the capsule carrying the micro-accelerometer is subjected to a pre-determined acceleration which results in an acceleration for the micro-accelerometer lying within the measuring range.

The ball pre-positioning condition, is obtained by means of the follower systems controlling the electrostatic position control devices.

According to a feature of the invention, the micro-accelerometer comprises three follower systems receiving input signals consisting of the electrostatic position detector signals and producing output signals applied to ball position control devices, at least one resistance and capacitor circuit, at least one current source to charge the said capacitor, and means for selectively connecting to the electrostatic ball position device relative to a given direction of the orthogonal axes system associated with the casing, either the follower system output relative to said given direction or the resistance and capacitor circuit.

By discharging the capacitor of the resistance and capacitor circuit across the capacitor formed by the ball and a circumpolar electrode, an electrostatic force proportional to the square of the discharge voltage and which decreases with the latter is produced. The energy thus generated can be adjusted by selecting the capacitance of the capacitor and its initial charge voltage and the speed at which the force decreases as a function of time can be adjusted by selecting the value of the resistance. In the case of the vertical direction, this electrostatic force is in the same direction as that of the weight. Then, the ball having been brought into its measuring field, an acceleration of given amplitude is produced.

According to another feature of the invention, the follower system relative to a given direction includes several amplifiers with different distributed gains and the said follower system includes means for selectively inserting one of these amplifiers in the follower system loop, these inserting means being, themselves, controlled by the acceleration measuring apparatus connected to the amplifier having a gain value immediately near the gain value of the amplifier to be inserted. In other words, when the measuring apparatus relative to a given portion of the total acceleration range reaches one end of its measuring scale, it transmits a signal which causes the insertion, into the follower system loop, of the amplifier which deals with the portion of the range adjacent to said given portion. It is thus possible to divide the measuring range into several sub-ranges each corresponding to an amplifier. As regards the follower system amplifier gain, it is only limited by the break-down voltage between the ball and the casing in vacuum.

The micro-accelerometer may compromise, apart from the ball, a moving mass and means for applying thereto an alternating rectilinear or circular movement. By suitably determining the weight of this mass and its movement it is possible to produce and apply to the accelerometer an acceleration of known amplitude.

The invention will now be described in detail with reference to the accompanying drawings in which:

FIG. 1 illustrates a first model of a capacitive accelerometer according to the invention shown in cross-section by a plane passing through the common center of the ball and spherical-casing and through the center of the two opposite surfaces forming the cubic outer surface of the casing;

FIGS. 2a, 2b and 2c, respectively, form an exploded view respectively showing the casing partially cut away, two of the electrode-support bushings and the ball of the accelerometer;

FIG. 3 is a front view of the accelerometer;

FIG. 4 is a cross-sectional view of an electrode-support bushing;

FIG. 5 is a cross-sectional view of the ball;

FIG. 6 illustrates the wiring diagram of the electrical system of the accelerometer including the position detecting means and the position control means;

FIG. 7 is a curve showing the variation of the spacing between the ball and the casing during free-fall;

FIG. 8 illustrates a perspective view of a second model of micro-accelerometer;

FIG. 9 is a perspective view of the open casing showing the ball within the casing;

FIG. 10 is a cross-sectional view of one of the electrode-support bushings containing the position detecting electrode and the position control electrode;

FIG. 11 is a perspective view of one of the cases containing a pre-amplifier connected to the position detecting electrode;

FIG. 12 illustrates the follower system line relative to the vertical direction comprising a resistance and capacitor circuit designed for pre-positioning the ball in its operative domain;

FIG. 13 illustrates the follower chain relative to the vertical direction comprising three amplifiers;

FIG. 14 illustrates the moving mass for calibration; and

FIG. 15 illustrates the generators of accelerations of predetermined amplitudes.

Referring to FIGS. 1, 2a, 2b, 2c and 3, reference numeral 1 designates a light ball polished and machined with very great accuracy (typical particulars of a ball will be given hereafter) and reference numerical 2 designates a casing with a cubic outer surface and a substantially spherical inner surface surrounding the ball. The casing should consist, theoretically, of the space included between a concentric outer cube and an inner sphere. In fact, for machining purposes and also to enable insertion of the ball in the casing, casing 2 consists of a space included between an outer cube and three cosecant cylindrical bores 3 the axes of which form a trihedral, the origin of which coincides with the center of the cube and the axes of which are perpendicular to the faces of the cube. The diameters of the three bores 3 are equal and slightly larger than the diameter of the ball. The interior of the casing unit is, therefore, not spherical and in fact the partially spherical interior surface of the casing results from suitably shaped bushings fitted in the bores.

Electro-support bushings 5 consisting of a circular plate 6, a cylindrical part 7, a conical part 8 and a bottom shaped in the form of a spherical re-entrant cap 9 can be inserted into bores 3. Thus the spherical surface of the casing only consists of six spherical caps with the remainder of the surface being cylindrical. This arrangement does not give rise to any serious disadvantage in the operation of the apparatus, since the casing exhibits cylindrical symmetry around each position detecting axis and each position controlling axis. However, since the direct potential of the ball is fixed by capacitance, fixing is improved with the increase in the capacitance of the capacitor formed by the ball and the casing. From this point of view, the second model of casing described in connection with FIG. 9 offers advantages over the first model being described at present.

A cylindrical housing 10 is machined into the spherical part of each electrode-support bushing. An insulating disk 11, made out of silicon oxide for example, a polar electrode 12 and a circumpolar electrode 13 both made out of stainless steel for example, are inserted into this housing. The electrodes are made to adhere to the insulating disk by means of a heat hardening resin and they are shaped in such a manner that the front surface has the shape, respectively, of a cap and a ring of spherical surface. The electrodes are equipped with connection terminals, 14 and 15 respectively, which pass through the support part 5 in insulated tubes 16 which are made out of steatite for

example. The circular plate 6 of the electrode-support member has a diameter slightly larger than that of the cylindrical portions 7 of this member thus forming a flange with its lower part resting on one of the surfaces of casing 2 and which is secured to this surface by means of screws 17.

It can be ascertained, in the structure just described, that the conducting ball 1 forms a first capacitor with the cylindrical metal wall of casing 2 and the interiors of the spherically shaped caps 9, which capacitor has of large capacitance through which the potential of the ball is fixed, a set of six second capacitors with the polar electrodes, which capacitors form the position sensors and a set of six third capacitors with the circumpolar electrodes which capacitors form the position control devices. The position detecting signal relative to one of the polar directions is picked-up between the two polar electrodes relative to this direction and the position control signal transmitted by the follower system corresponding to this detection signal, is applied between the two circumpolar electrodes surrounding said polar electrodes.

A section of the ball is illustrated in FIG. 5. It may be seen that it is hollow and that it consists of two hemispheres 18 and 18' fitted into each other. The leading particulars of a typical ball are as follows:

Diameter: 39.974 mm.

Weight: 33.80 gr.

Maximum spherical tolerance: 0.5 μ .

The space between ball and casing, in the case where the ball and the casing are concentric can decrease down to a few tens of μ . The applicant has made apparatuses in which the value of the gap was, respectively, 100 μ and 10 μ .

FIG. 6 illustrates the wiring diagram of the accelerometer in the form of a block diagram for one coordinate of the trihedral. There are, therefore, two other chains which are identical to that illustrated.

The capacitors formed by electrodes 12 and 12' and ball 1 form part of a measuring bridge including two resistances 19 and 19' and the bridge is supplied by generator 20 between the common point of the two resistances 19 and 19' and the casing. The unbalanced signal of the bridge is amplified in amplifier 21 and detected in synchronous detector 22. The detected signal is applied to a correcting network 23 then to a differential amplifier 24 and the two output signals, which have the form $V_0 \pm kv$ (where k is a constant and v a voltage proportional to the displacement of the ball) are applied to the two circumpolar electrodes 13 and 13'. In one example of an accelerometer made by the applicant, the frequency of the generator 20 was 50 Hz., the power supply voltage of the order of 1 volt R.M.S. Voltage V_0 can be alternating and in the same model of accelerometer, the R.M.S. value of this voltage V_0 was taken to be equal to 10 volts. Although this is not, in fact, necessary, it is possible to separate the actuations in the three follower directions by supplying the sensing electrodes from generators with different frequencies and by placing band filters corresponding to these frequencies before amplifiers 21.

It is also possible to obtain separation of actuation in the three directions by supplying the electrodes corresponding to each of the three axes with three phase voltages. Under these conditions, the addition of the three residual potentials on the ball gives a zero resultant.

The general expression of the electrostatic forces on the ball is:

$$F = \frac{\epsilon_0 S}{2} \frac{(V_0 + v)^2}{(e - z)^2} - \frac{(V_0 - v)^2}{(e + z)^2}$$

where e and ϵ_0 have already been defined, z is the distance from the center of the spherical casing to the actual center of the ball and S is the surface of the actuating electrode.

Around the operational point, the following is obtained:

$$\Delta F = \frac{\delta F}{\delta z} dz + \frac{\delta F}{\delta v} dv = az + bv \quad (1)$$

by effecting a change in variables $dz=z$ and $dv=v$ and by stating:

$$a = \frac{\delta F}{\delta z} = 2\epsilon_0 S \frac{V_0^2}{e^3}; \quad b = \frac{\delta F}{\delta v} = 2\epsilon_0 S \frac{V_0}{e^2}$$

The expression of ΔF shows the instability of the balance since a and b are both positive.

In order to obtain stable operation, it is necessary to make a follower system with a corrector network. The general diagram of such a follower system is illustrated in FIG. 6.

If:

m = the weight of the ball;

u = the output voltage of the synchronous detector 22;

k = the constant linking u to the displacement z of the ball;

u_0 = the reference potential corresponding to the original position of the ball;

α = the signal error;

G = the gain of amplifier 24.

The follower system equations without a corrector system are, apart Equation 1, the following:

$$\alpha = u_0 - u \quad (2)$$

$$v = G\alpha \quad (3)$$

$$\frac{m d^2 z}{dt^2} = az + bv \quad (4)$$

When the ball is maintained at the origin by the servomechanism, $u_0=0$. The solution of Equations 2 to 4 gives:

$$m \frac{d^2 u}{dt^2} + (bGk - a) = 0$$

The solution of this differential equation is nondivergent for

$$-a + bGk > 0$$

$$Gk > a/b$$

To obtain a convergent solution, it is necessary to introduce a term of damping which is given by corrector network 23.

Referring now to FIG. 8, the micro-accelerometer comprises a casing which is no longer cubic but spherical 51 consisting of two hemispheres 52 and 53 each with a flange 54. These two hemispheres are fixed together by means of screws 55 through threaded holes 56.

By taking as poles of the sphere the points where the position detecting electrodes relative to the vertical axis are located, the flanged portions 54 are not located in an equatorial plane, that is to say that the poles of the hemispheres are not the poles of the casing. A line perpendicular to the equatorial plane of the hemispheres makes angles of $54^\circ 45'$ (angle of the diagonal of a cube with the edges of the cube) with the axes joining the centers of the diametrically opposed polar electrodes.

Casing 51 is attached to plate 57 by means of two oblique consoles or brackets 58 (only one of the two brackets is shown in FIG. 8), which are screwed by one extremity to the plate and carry, at the other extremity, a groove 59 in which the edges 54 of the hemispheres are inserted and attached.

The two hemispheres include exterior tubes 60 and 61 which are perpendicular to their common diametral plane and which serve as a mandrel during machining. One of these tubes 61 is blocked and the other 60 is coupled to ionic pump 62. This pump is supported with respect to plate 57 by a bent fitting 63. It receives power supply through connector 64 by means of a supply line (not shown).

Sphere 51 carries six reamed drillings or bores the axes of which are aligned in pairs forming a trihedral. A bushing 65 (FIG. 10) is inserted into each bore. The inner part of bushing 65 comprises a first recess 66 and a second recess 70. Inside recess 66 is located a central electrode 67 in the form of a cylinder the front surface 68 of which is given the shape of a re-entrant spherical cap and the rear surface of which is prolonged by an extension pin 69. Inside recess 70 is located a peripheral electrode 71 shaped in the form of a ring the front profile 72 of which is hollowed out to form a re-entrant spherical segment and which is provided with a connection pin 73. These two electrodes are insulated from bushing 65 by means of an insulating and sealing material 74 such as glass, ceramics or heat hardened resin. The two housings 66 and 70 are separated by a spacer ring or guard ring 75. The purpose of this ring is to uncouple the capacitor between the position detecting electrode and the ball from the capacitor between the position control electrode and the ball. Connection wires 69 and 73 terminate at a connector 76. There are, therefore, six connectors 76 on the sphere, only one of them being shown in FIG. 9.

The connection between connectors 76 and the follower system circuits is effected, in the case of each follower system direction by means of brackets (FIG. 11). There are three of these brackets 81, 82, 83 and each consists of two parallel tubes 77 and 78 connected by a flat box 79. This box contains the pre-amplifier from which each follower system starts (this pre-amplifier forms part of amplifier 21 in FIG. 6). Tubes 77 and 78 are provided with slots 84 in which the connectors 76 penetrate. These are attached to plate 57 by brackets such as bracket 85.

Referring now to FIG. 12, a follower chain is shown the different circuits of which are designated by the same reference numerals as in FIG. 6 and furthermore, there are represented a direct current source 39 connected in parallel to the terminals of a capacitor 40, to a resistance 41 and to the position control electrodes 13-13' relative to the vertical axis. The acceleration measuring apparatus connected to the differential amplifier 24 is designated by the reference numeral 100. A first switch 42 is placed in series with the current source 39; a second switch 43 is placed in series with resistance 41; a third switch 44 is inserted between the pre-positioning circuit and the ball position control electrodes 13-13' and a fourth switch 45, finally, is inserted between the output of amplifier 24 in the follower chain and the said position control electrodes.

The various switches are controlled by a programming unit 46 in accordance with the following program starting from instant t_0 when the capsule in which the micro-accelerometer is placed is released.

- (a) before instant t_0 when the capsule is released: closing of 42 for a sufficient time to charge capacitor 40 and thereafter opening 42
- (b) instant $(t_0 - \epsilon)$: 44 closes
- (c) instant $(t_0 + \epsilon)$: 43 closes
- (d) instant $(t_0 + t_1)$: 43, 44 open; 45 closes

Since the follower system loop must only be closed when the ball is within its measuring range, programming unit 46 only passes to stage D when the measuring unit 100 is, itself, within its measuring range.

In the second pre-positioning system, the sensitivity is modified during free-fall in such a manner as to pass from g to $10^{-9} g$ during the fraction $(t_1 - t_0)$ of time spent in free-fall. By referring to FIG. 13, three circuits 47, 48, 49 have been shown which each include a corrector circuit 23₁, 23₂, 23₃ respectively and a differential amplifier 24₁, 24₂, 24₃ respectively. These amplifiers have different gains and an operational range of 10^3 . The first amplifier 24₁ serves for the acceleration range $g-10^{-3} g$, the second 24₂ for the acceleration range $10^{-3} g-10^{-6} g$ and the third 24₃ for the accelera-

tion range 10^{-6} g- 10^{-9} g. Since the forces applied to the ball are proportional to the square of the voltages, the three amplifiers have gains with ratios of $\sqrt{10^{-3}}$. Amplifier 24₁ has a gain such that it is capable of supplying at maximum, an output signal of the order of 5000 volts and amplifiers 24₂, 24₃ can deliver output signals of the order of 150 and 5 volts respectively.

The three differential amplifiers 24₁, 24₂, 24₃ are associated with measuring units 99₁, 99₂, 99₃. The measuring units are connected to a programming unit 86 and are provided with means for indicating that they are at the lower limit of their measuring range. Such means may consist of an electrical contact.

A three position switch 50, which is controlled by programming unit 86 is inserted between the output of the synchronous detector 22 and assemblies 47, 48, 49. At the moment of release t_0 the switch is in position 50₁, then it passes, successively, to position 50₂ and 50₃ at the moments when measuring units 99₁, 99₂, arrive, respectively, at the lower limit of their measuring range in such a manner that, at instant t_1 , only assembly 49 is in service;

FIG. 14 represents the vibrator designed to give the micro-accelerometer an acceleration of a known value directed along one of the directions of the three orthogonal planes associated with the casing. It is attached to a plate 87 which can be secured by posts 88, to plate 57 of the micro-accelerometer in such a manner that the vibrational direction of the vibrator is in alignment with the direction of the micro-accelerometer under consideration. Posts 88 are screwed into the threaded holes in plate 57 one of which 95 is shown in FIG. 8. The vibrator includes a magnetic circuit in the form of a pot 89, an inner winding 90, a plunger core manufactured out of a suitable magnetic material 91 coaxial with winding 90 and a pole piece 92 attached to the heel piece in front of the plunger core. Core 91 is attached to the heel piece by means of two flexible disks 93 and 94. When the coil is supplied with alternating current, core 91 vibrates at the frequency of this current. The amplitude of the acceleration is measured at terminals 98 of the capacitor formed by pole piece 92 and a plate 101 carried by disk 94.

For example, if it is assumed that the weight of core 91 is 1 gr., that the weight of the capsule containing the micro-accelerometer is 100 kg. and that the frequency of the power supply current is 1.5 Hz., the acceleration γ_0 applied to the micro-accelerometer by the core subjected to an acceleration γ_1 is

$$\gamma_0 = 10^{-5} \gamma_1$$

If it is desired to apply an acceleration of 10^{-7} g, for example, to the micro-accelerometer, it will be necessary that $\gamma_1 = 10^{-2}$ m. sec.⁻² that is to say that the amplitude of the vibration of the vibrator is

$$1/10^2 \times 4\pi^2 \times 1.5 = 0.9 \text{ mm.}$$

Switching of current into winding 90 is controlled at instant t_1 by programming unit 46 or programming unit 86 which closes contact 96 connecting the alternating current source 97 to winding 90.

In order to calibrate the accelerometer along the three axes of the trihedron associated with the casing, two other vibrators, identical to that which has just been described, are associated with the micro-accelerometer. FIG. 15 illustrates the arrangement of plates 87, 102, 103 of these vibrators relative to micro-accelerometer plate 57 in such a manner that the vibrational directions are aligned with the directions of the three orthogonal axes of the trihedron associated with the casing. It can be seen that plate 102 is attached to plate 57 by means of a angle-iron 104 and two posts 105 and that plate 103 is attached to plate 57 by means of a angle-iron 106 and two posts 107.

FIG. 7 shows a curve 26 illustrating the recording

of the relative movement of the ball with respect to the casing during a test in free-fall. It may be seen that passage to zero takes place approximately fifteen milliseconds after the beginning of the experiment.

What we claim is:

1. Electrostatic accelerometer providing an integrated measure of acceleration along three orthogonally arranged axes comprising a hollow casing substantially spherical at its inner side having electrical conductivity, a spherical acceleration sensing mass having electrical conductivity and freely floating in said casing in gravity free condition when not subjected to acceleration, three opposed pairs of polar electrodes isolated from the casing and located in orthogonal relation on the inner casing surface to provide the axes of the accelerometer, said polar electrodes forming with the spherical mass outer surface six first capacitors adapted to detect the position of said mass, three opposed pairs of circumpolar electrodes isolated from the casing and respectively surrounding the polar electrodes, said circumpolar electrodes forming with the spherical mass outer surface six second capacitors adapted to control the position of said mass, the inner surface of the casing and the outer surface of the spherical mass forming a third capacitor having a capacitance highly larger than that of the first and second capacitors, means for applying an alternating current between said casing and respectively said polar electrodes, means connected to said polar electrodes for providing output signals depending on the displacement of the mass along the orthogonal axes from a centered position and associated with said axes, means for detecting and amplifying said signals and means for applying the detected and amplified signals associated with the orthogonal axes respectively to the circumpolar electrodes corresponding to said axes.

2. Electrostatic accelerometer as claimed in claim 1 in which said position detecting polar electrodes and position controlling circumpolar electrodes are separated by guard rings brought to the electrical potential of the spherical mass.

3. Electrostatic accelerometer as claimed in claim 1 in which the casing comprises two hemispheres connected to each other by flanged portions arranged in a common diametral plane and the polar and circumpolar electrodes are located in each hemisphere at the intersection points of said hemisphere with orthogonal axes centered at the end of the radius of the hemisphere perpendicular to the common plane and forming with said radius an angle equal to that formed by the edges of a cube with its diagonal.

4. Electrostatic accelerometer as claimed in claim 1 comprising means for applying a vacuum to the space comprised between said hollow casing and said spherical mass.

5. Electrostatic accelerometer providing an integrated measure of acceleration along three orthogonally arranged axes in a given range of accelerations divided into sub-ranges comprising a hollow casing substantially spherical at its inner side having electrical conductivity, a spherical acceleration sensing mass having electrical conductivity and floating freely in said casing in gravity free conditions and when not subjected to acceleration, three opposed pairs of polar electrodes isolated from the casing and located in orthogonal relation on the inner casing surface to provide the axes of the accelerometer, said polar electrodes forming with the spherical mass outer surface six first capacitors adapted to detect the position of said mass, three opposed pairs of circumpolar electrodes isolated from the casing and respectively surrounding the polar electrodes, said circumpolar electrodes forming with the spherical mass outer surface six second capacitors adapted to control the position of said mass, the inner surface of the casing and the outer surface of the spherical mass forming a third capacitor having a capacitance highly larger than that of the first and second capacitors, means connected to the polar electrodes for applying an alternat-

ing current between said casing and respectively said polar electrodes, means for providing output signals depending on the displacement of the mass along the orthogonal axes from a centered position and associated with said axes, means for detecting said signals, a plurality of amplifiers connected between said detecting means and said circumpolar electrodes and having different gains forming a discrete sequence of gains for amplifying said detected signals, means for selectively operating one of said amplifiers between said detecting means and respectively the circumpolar electrodes and means for measuring the output signals of said amplifiers, whereby the output signal of a given amplifier measures the acceleration acting upon the sensing mass in an acceleration sub-range depending on the gain of the inserted amplifier.

6. Electrostatic accelerometer as claimed in claim 5 in which the means for measuring the output signal of a given amplifier connected between the detecting means and the circumpolar electrodes comprises means for generating a switching signal when said measuring means are at one end of the sub-range thereof and means for controlling by said switching signal the selective operating means, thereby inserting between the detecting means and respectively the circumpolar electrodes the amplifier having, in the discrete sequence of gains, a gain nearly adjacent to that of said given amplifier.

7. Electrostatic accelerometer providing an integrated measure of acceleration along three orthogonally arranged axes comprising a hollow casing substantially spherical at its inner side having electrical conductivity, a spherical acceleration sensing mass having electrical conductivity and floating freely in said casing in gravity free condition and when not subjected to acceleration, three opposed pairs of polar electrodes isolated from the casing and located in orthogonal relation on the inner casing surface to provide the axes of the accelerometer, said polar electrodes forming with the spherical mass outer surface six first capacitors adapted to detect the position of said mass, three opposed pairs of circumpolar electrodes isolated from the casing and respectively surrounding the polar electrodes, said circumpolar electrodes forming with the spherical mass outer surface six second capacitors adapted to control the position of said mass, the inner surface of the casing and the outer surface of the spherical mass forming a third capacitor having a capacitance highly larger than that of the first and second capacitors, means for applying an alternating current between said casing and respectively said polar electrodes, means connected to the

polar electrodes for providing output signals depending on the displacement of the mass along the orthogonal axes from a centered position, means for detecting and amplifying said signals, a resistance and capacitor discharge circuit, a current source for charging said capacitor of said latter circuit and means for selectively applying to the circumpolar electrodes the detected and amplified signals associated with the orthogonal axes and said resistance and capacitor discharge circuit.

8. Electrostatic accelerometer providing an integrated measure of acceleration along three orthogonally arranged axes comprising a hollow casing substantially spherical at its inner side having electrical conductivity, a spherical acceleration sensing mass having electrical conductivity and floating freely in said casing in gravity free condition and when not subjected to acceleration, three opposed pairs of polar electrodes isolated from the casing and located in orthogonal relation on the inner casing surface to provide the axes of the accelerometer, said polar electrodes forming with the spherical mass outer surface six first capacitors adapted to detect the position of said mass, three opposed pairs of circumpolar electrodes isolated from the casing and respectively surrounding the polar electrodes, said circumpolar electrodes forming with the spherical mass outer surface six second capacitors adapted to control the position of said mass, the inner surface of the casing and the outer surface of the spherical mass forming a third capacitor having a capacitance highly larger than that of the first and second capacitors, means connected to the polar electrodes for applying an alternating current between said casing and respectively said polar electrodes, means for providing output signals depending on the displacement of the mass along the orthogonal axes from a centered position and associated with said axes, means for detecting and amplifying said signals, means for applying the detected and amplified signals associated with the orthogonal axes respectively to the circumpolar electrodes corresponding to said axes and means for submitting the accelerometer to predetermined accelerations.

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