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May 19, 1970 G. G. NORTH 3,512,852

STABILIZED LEVITATION OF MAGNETIC ELEMENTS

Filed March 7, 1969 2 Sheets-Sheet 1

Fig. 1.

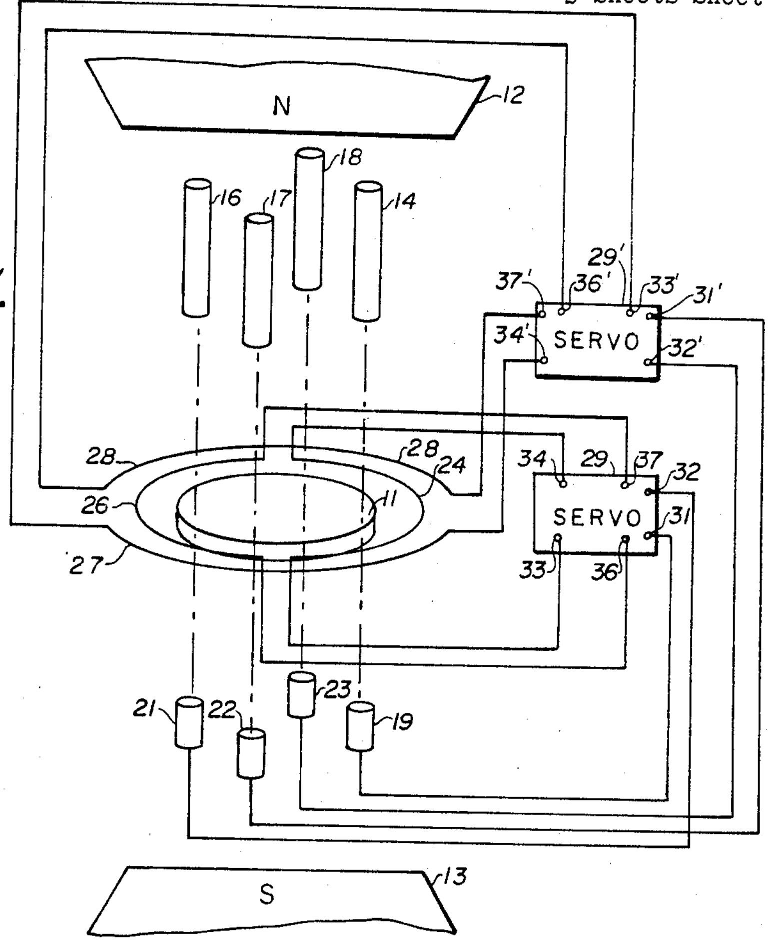

Fig. 5.

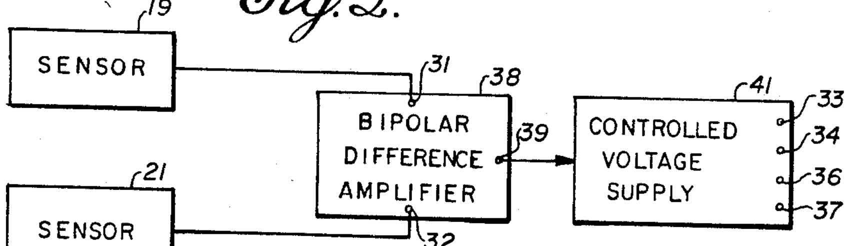

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Fig. 2.

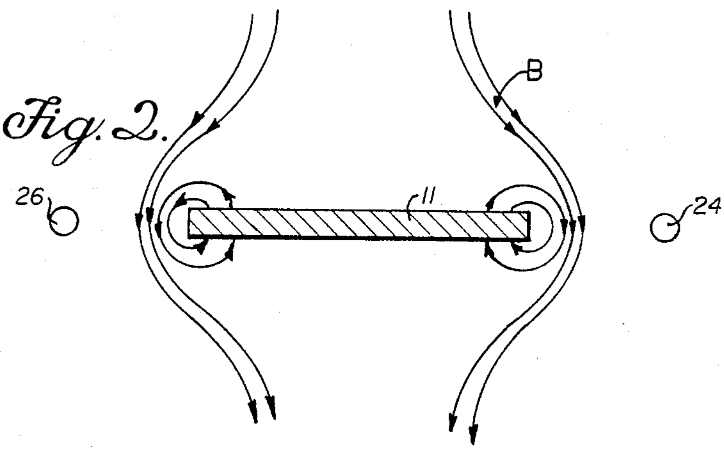


Fig. 3.

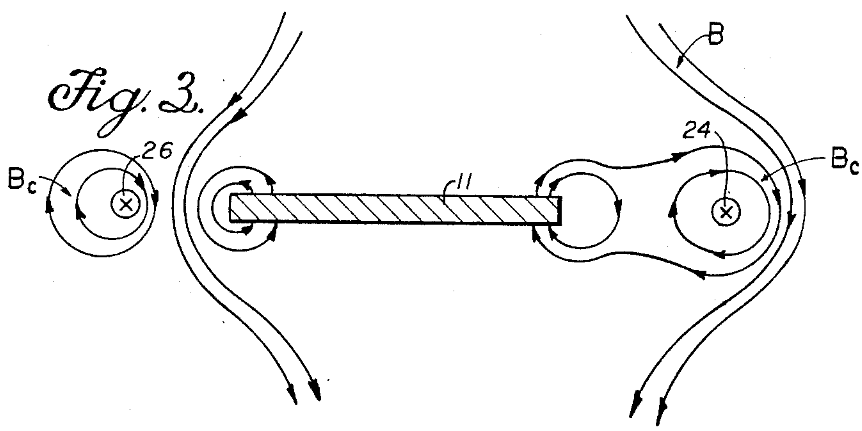
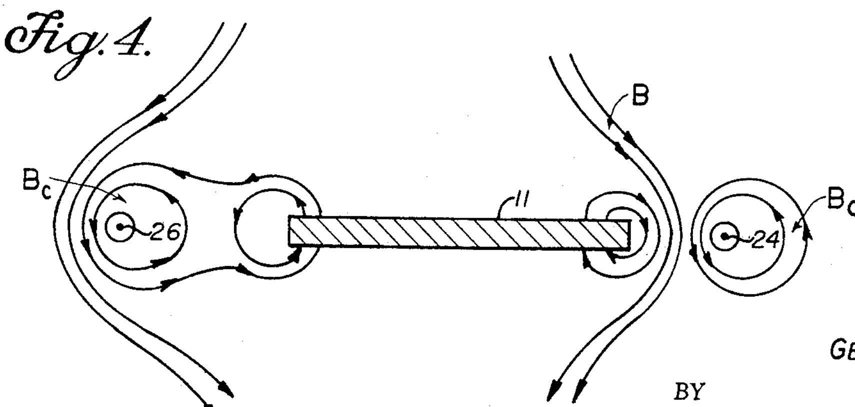


Fig. 4.



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3,512,852
STABILIZED LEVITATION OF MAGNETIC ELEMENTS

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Int. Cl. F16c *39/06*
Int. Cl. 308—10 5 Claims

ABSTRACT OF THE DISCLOSURE

A system for stabilizing a magnetic element, such as as a magnetized disc, conductive ring having a circulatory current therein, or the like, levitated in a magnetic field, against movement out of a region of free suspension therein. The magnetic element is positioned with its magnetic field in opposition to a vertically oriented magnetic levitation field such that the fields interact to freely support the element against the forces of gravity. Any tendency of the element to slip laterally from its stable support position to unstable support positions is continuously sensed and responsively compensated by the generation of a magnetic compensating field which is effective to restore the element to, and thereby maintain the element in, its stable support position.

BACKGROUND OF THE INVENTION

This invention was evolved under, or in the course of Contract W-7405-eng-48 with the United States Atomic Energy Commission.

Under various circumstances it is desirable to levitate a magnetic element, such as a magnetized disc or current carrying conductive ring, in a magnetic levitation field. A non-materially supported magnetized disc freely suspended in space is, of course, advantageously employable as a platform for supporting objects out of thermal, electrical, and frictional contact with adjacent or surrounding material surfaces. Likewise in various controlled thermonuclear reaction research devices it is necessary to freely suspend a current carrying conductive ring within an ionized plasma magnetically confined within a toroidal chamber. In particular, free suspension of a superconducting closed loop, having a large order circulatory current induced therein, within a confined plasma permits build-up of a hot ion plasma.

It will be appreciated that in the case of both the magnetized disc and current carrying ring types of magnetic elements, the associated magnetic fields are similar. One face of the element is magnetized with north polarity while the opposite face is magnetized with south polarity, and the lines of flux are directed from the north pole face to the south pole face in symmetrically disposed reentrant loops extending about the periphery of the disc parallel to its axis. Such an element is consequently levitated when it is disposed with its associated magnetic field in opposition to a vertically oriented uniform magnetic levitation field, as may be generated, for example, by spaced-apart, vertically aligned, oppositely polarized magnetic pole pieces. In this regard the magnetic element is disposed in the levitation field with the north and south faces of the element respectively facing the north and south pole pieces. By virtue of the opposed fields, magnetic forces are generated which offset the downwardly directed gravitational force acting on the element. The element assumes an equilibrium position of free suspension in the vertical direction. However, a condition of severe instability exists in the lateral retention of the element in suspended position. The interacting magnetic fields have associated forces that are such as to cause

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the element to slip laterally from a substantially centered position in the levitating field, and to invert itself, thereby terminating levitation. Thus, in the absence of means for overcoming the lateral instability in the support of the element, levitation thereof is short lived.

SUMMARY OF THE INVENTION

The present invention relates to the stabilized levitation of a magnetic element of the previously described type in a magnetic levitation field in order to provide steady-state, non-material suspension of the element.

In the accomplishment of the foregoing, the invention is arranged to continuously restore the magnetic element to a stable substantially centered position in the levitating field in response to any tendency of the element to slip laterally therefrom. More particularly, the invention includes means for sensing lateral displacements of the magnetic element from centered position in the magnetic levitation field, and means responsive to the sensed displacements for generating a compensating magnetic field peripherally about the element having a direction and magnitude to adjust the configuration of the field of the element and the levitation field in a manner productive of force opposing the displacements to thereby restore the element to its centered position.

BRIEF DESCRIPTION OF THE DRAWING

FIG. 1 is a schematic representation of a system for the stabilized levitation of magnetic elements in accordance with the present invention.

FIGS. 2–4 are graphical illustrations depicting the manner in which the system of the present invention is effective to stabilize the levitation of a magnetic element.

FIG. 5 is a block diagram of one of the servos employed in the system of FIG. 1.

DESCRIPTION OF THE PREFERRED EMBODIMENT

Referring now to FIG. 1, there is shown a system in accordance with the present invention for stabilizing the levitation of a magnetized disc **11**, or equivalent magnetic element, such as a current carrying conductive ring, in a uniform vertically oriented magnetic levitation field generated, for example, by spaced-apart vertically aligned, oppositely polarized magnetic pole pieces **12** and **13**. The opposite faces of the disc are oppositely magnetically polarized such that the disc has an associated magnetic field with magnetic flux directed from the north pole face to the south pole face in symmetrically disposed reentrant loops extending about the periphery of the disc parallel to the axis thereof. The levitation field is defined by uniformly distributed axially symmetric lines of magnetic flux directed vertically from the north pole piece **12** to the south pole piece **13**. The disk is coaxially disposed between the pole pieces with the field of the disc opposing the levitation field, i.e., with the north and south faces of the disc respectively facing the north and south pole pieces. The fields interact and establish repulsive vertical magnetic forces which offset the downwardly directed gravitational force acting on the disc. The disc is thus freely suspended in the vertical direction by the cancellation of forces.

With the disc precisely centered on the pole piece axis, the composite magnetic field due to the interacting disc field and levitation field has lines of flux B with a configuration substantially as depicted in FIG. 2. In this regard, the flux lines are axially symmetric and bulge outwardly about the disc periphery. It will be appreciated that with such a symmetric field configuration, the lateral, as well as the vertical components of magnetic force are balanced such that the disc is in a position of stable support. Howeven, any departure of the disc from precisely centered position distorts the symmetry of the outwardly bulging portion of the flux lines. There is an attendant unbalance of the lateral components of force acting on the disc such that it slips in the lateral direction away from centered position. Thereafter the disc is inverted, thereby terminating levitation.

It will be appreciated that the field configuration depicted in FIG. 2 capable of stably supporting the disc represents a singular idealized condition requiring precise centering of the disc in the levitation field and precise uniformity of the disc field and levitation field. Such a singular condition is virtually impossible to obtain and maintain in actual practice by virtue of material imperfections in the disc and pole pieces, field perturbations, and the like. Consequently it may be said that support of the dics, while being stable in the vertical direction, is unstable in the lateral direction. There is a severe tendency for the disc to slip laterally in the levitation field away from a centered position of totally stable support such that levitation of the disc is extremely short lived.

To overcome the foregoing problem, the stabilizing system of the present invention basically includes position sensing means arranged to sense departures of the disc **11** from a laterally centered position coaxially between the pole pieces **12** and **13**, and to signal the direction and extent of such departures. The sensed position signals are employed to actuate magnetic compensating field generating means operable to adjust the configuration of the composite disc and levitation field in a manner productive of magnetic force opposing the sensed departures and restoring the disc to centered position. More particularly, the position sensing means are preferably provided as a plurality of light sources **14**, **16**, **17**, and **18** disposed in vertically spaced relation to one face of the disc to beam light towards a plurality of photocells, or equivalent light sensors **19**, **21**, **22**, and **23** disposed in vertically spaced relation to the opposite face of the disc in corresponding alignment with the light sources. The light sources and sensors are equally radially spaced outwardly from the axis of the pole pieces at 90° circumferentially spaced intervals adjacent the periphery of the disc.

Thus, when the disc is in its centered position diametrically opposed sensors **19** and **21** are exposed to equal amounts of light from their associated sources **14** and **16**, while diametrically opposed sensors **22** and **23** are exposed to equal amounts of light from their associated sources **17** and **18**. However, when the disc slips laterally from its centered position, a sensor of at least one of the diametrically opposed pairs thereof is exposed to more light from its associated source than the light the other sensor of the pair is exposed to from its associated source. This is by virtue of the disc masking less light from the former sensor and more light from the latter sensor by moving away from, and towards the respective light beams directed thereon. It will be thus appreciated that the direction and magnitude of lateral displacement of the disc is indicated by the extents to which the respective sensors are exposed to their associated light sources. Inasmuch as the sensors generate electrical signals in proportion to the amount of light incident thereon, the signals are representative of disc position. More particularly, the algebraic difference between the signals generated by the sensors of each diametrically opposed pair thereof is indicative of the direction and magnitude of the component of disc movement from centered position along that particular diameter. Thus, when the disc is in centered position such that opposed sensors **19** and **21** are exposed to the same amounts of light and opposed sensors **22** and **23** are exposed to the same amounts of light, the algebraic differences between the resulting signals are zero. However, if, for example, the disc moves from right to left, as viewed in FIG. 1, along a diameter aligned with opposed pair of sensors **19** and **21**, sensor **19** is exposed to more light than sensor **21**. The algebraic difference between the sensor signals is then positive and of a magnitude proportional to the extent of disc displacement from centered position. Conversely, if the disc moves from left to right, sensor **21** is exposed to more light than sensor **19**. The algebraic difference between the sensor signals is then negative and of a magnitude proportional to the extent of disc displacement from centered position. Similarly, the polarity of the algebraic difference between the signals from opposed sensors **22** and **23** indicates movement of the disc into or out of the plane of FIG. 1, while the magnitude indicates the extent of such movement. Combinations of the differences between the signals from the respective diametrically opposed pairs of sensors indicate lateral movement of the disc in directions other than those in alignment with the opposed pairs of sensors.

Considering now the compensating field generating means in detail and the manner in which the sensor signals are employed to control same, it is to be noted that the compensating field generating means preferably include a pair of opposed arcuate conductors **24** and **26**, each extending substantially 180°, coaxially disposed with respect to pole pieces **12** and **13** in outwardly spaced circumscribing relation to disc **11**. Also included is a second pair of opposed arcuate conductors **27** and **28**, each extending substantially 180°, coaxially disposed with respect to the pole pieces in outwardly spaced circumscribing relation to the disc and circumferentially displaced from the conductors **24** and **26** by 90°. Upon the flow of current through the conductors, magnetic flux is generated concentrically thereabout. The sense and magnitude of the compensating flux is determined by the direction and magnitude of current flow through the conductors. The compensating flux interacts with the composite disc and levitating field and alters the configuration thereof peripherally of the disc in accordance with the sense and magnitude of such flux. Thus, the sense and magnitude of the compensating flux may be controlled to produce magnetic forces effective to return the disc to centered position whereupon field symmetry is restored.

In the accomplishment of the foregoing, the signals from the opposed pair of sensors **19** and **21** and pair of sensors **22** and **23** indicating the direction and extent of lateral displacements of the disc **11** from centered position are employed to control the direction and magnitude of current flow in the opposed pair of conductors **24** and **26**, and opposed pair of conductors **27** and **28**, respectively to generate compensating flux in a manner to overcome the sensed disc displacements. More particularly, a servo **29** is provided with input terminals **31** and **32** respectively connected to sensors **19** and **21**, a first pair of controlled voltage supply terminals **33** and **34** respectively connected to the opposite ends of conductor **24**, and a second pair of controlled voltage supply terminals **36** and **37** respectively connected to the opposite ends of conductor **26**. Similarly, there is provided a second zero **29'** having input terminals **31'** and **32'** respectively connected to sensors **22** and **23**, a first pair of controlled voltage supply terminals **33'** and **34'** respectively connected to the opposite ends of conductor **27**, and a second pair of controlled voltage supply terminals **36'** and **37'** respectively connected to the opposite ends of conductor **28**. The servo **29** is arranged such that in response to the signal at terminal **31** from sensor **19** being greater than the signal at terminal **32** from sensor **21**, voltages are generated at supply terminals **33** and **34** and at supply terminals **36** and **37** with polarities and magnitudes to drive currents through conductors **24** and **26** having appropriate directions and magnitudes to establish magnetic compensating flux with the proper sense and magnitude to laterally move the disc towards the sensor **19** supplying the greatest signal. Conversely, in response to the signal at terminal **32** from sensor **21** being greater than the signal at terminal **31** from sensor **19**, the polarities of the voltages generated at supply terminals **33** and **34** and at supply terminals **36** and **37** are reversed and the magnitudes are appropriate to effect lateral movement of the disc toward sensor **21** to centered position. Similarly, the servo **29′** is effective to control the directions and magnitudes of current flow through conductors **27** and **28** in accordance with the signals from sensors **22** and **23** to establish the proper sense and magnitude of compensating flux to laterally move the disc to centered position toward the sensor generating the greatest signal.

To the foregoing ends, the servo **29** is advantageously provided as illustrated in FIG. 5, and it is to be understood that the servo **29′** is provided in a similar manner. Servo **29** preferably includes a bipolar difference amplifier **38**, the differential input terminals of which correspond to terminals **31** and **32** and are thus respectively connected to sensors **19** and **21**. The amplifier functions to produce at an output terminal **39** thereof, a bipolar signal proportional to the algebraic difference between the sensor signals applied to terminals **31** and **32**. For example, in the illustrated case a positive signal having a magnitude proportional to the difference between the sensor signals is produced at terminal **39** in response to the signal from sensor **19** being greater than the signal from sensor **21**, whereas a negative signal having a magnitude proportional to the difference between the sensor signals is produced at terminal **39** in response to the signal from sensor **21** being greater than the signal from sensor **19**. When both sensor signals are equal, the signal at terminal **39** is zero.

The output terminal **39** of the difference amplifier is coupled to a controlled voltage supply **41** having two sets of supply terminals respectively corresponding to terminals **33** and **34** and to terminals **36** and **37**. The supply **41** functions to generate voltages at the output terminals having polarities and magnitudes in accordance with the algebraic difference signal applied thereto from the difference amplifier **38**. In addition, the supply is arranged such that the voltages at terminals **33** and **36** and at terminals **34** and **37**, respectively connected to adjacent ends of the conductors **24** and **26**, are simultaneously of the same polarities. In the illustrated case, a positive difference signal is productive of proportional supply voltages with positive polarities at terminals **33** and **36** with respect to terminals **34** and **37**. A negative difference signal is productive of proportional supply voltages of reversed polarities, i.e., negative polarity voltages at terminals **33** and **36** with respect to terminals **34** and **37**. Servo **29′** operates in a similar manner such that in response to the signal from sensor **22** being greater than that from sensor **23**, voltages proportional to the difference therebetween are produced with positive polarities at terminals **33′** and **36′** with respect to terminals **34′** and **37′**. When the signal from sensor **23** is greater than that from the sensor **22**, voltages proportional to the difference therebetween are produced with negative polarities at terminals **33′** and **36′** with respect to terminals **34′** and **37′**.

Considering now the overall operation of the levitation stabilizing system, assume that the disc **11** is in its centered position of coaxial alignment with the pole pieces **12** and **13**, as shown in FIG. 2. As previously noted, the flux lines B of the resulting composite field are axially symmetric and bulge outwardly about the disc periphery when the singular condition of both vertically and laterally stable disc support exists. The sensors **19** and **21** are exposed to equal intensities of light from sources **14** and **16**, and no signals are applied from the sensors to servo **29**. Thus, no current flows through conductors **24** and **26** and no compensating flux is thereby generated.

If the disc slips laterally to the left from centered position, as shown in FIG. 3, sensor **19** is exposed to more light from source **14** while less light from source **16** is received by sensor **21**. By virtue of the difference between the signals applied to the input terminals of servo **29**, the servo effects proportional counterclockwise current flow through conductor **24** and proportional clockwise current flow through conductor **26**, as depicted by the x's in the figure. Clockwise compensating flux B_c is thus generated concentrically about the conductors. It is to be noted that the compensating flux B_c, being directed clockwise, interacts with the composite field B in such a manner as to increase the density of flux lines on the left periphery of the disc and reduce the density of flux lines on the right periphery thereof. The attendant magnetic forces are thus such as to urge the disc towards the right to centered position. As the disc masks more and more of sensor **19** from the light beam directed from source **14**, and exposes sensor **21** to more and more of the light beam directed from source **16**, the compensating flux B_c is correspondingly reduced and is terminated when the disc reaches its centered position.

Conversely, if the disc slips laterally to the right from centered position, as shown in FIG. 4, sensor **21** is exposed to more of the light beam from source **16** while less of the light beam from source **14** is exposed to sensor **19**. The difference between the signals applied to the input terminals of servo **29** is now such that the servo effects proportional clockwise current flow through conductor **24** and proportional counterclockwise current flow through conductor **26**, as depicted by the dots in the figure. As a result, counterclockwise compensating flux B_c is generated concentrically about the conductors and interacts with the composite field B to increase the density of flux lines on the right periphery of the disc and decrease the density of flux lines on the left periphery thereof. Thus, the magnetic forces developed are such as to urge the disc towards the left to centered position.

In a similar manner, the sensors **22** and **23**, servo **29′**, and conductors **27** and **28** operate to stabilize the disc against movement laterally into and out of the plane of FIGS. 2–4. Simultaneous operation of the servos **29** and **29′** may, of course, also occur to effect current flow in both sets of conductors **24**, **26** and **27**, **28** having appropriate magnitudes and directions to stabilize the discs against movement in directions other than directly between the opposed sets of sensors. Stabilization of the lateral position of the disc is thereby continuously effected and levitation thereof is preserved.

I claim:

1. A stabilized magnetic levitation system comprising means for generating a uniform axially symmetric vertically oriented magnetic levitation field, a magnetic element generating a magnetic field with flux directed in symmetrically disposed reentrant loops extending about the periphery of the element parallel to the axis thereof, said element coaxially disposed in a centered position within said levitation field with the field of the element opposing said levitation field to thereby levitate said element therein, position sensing means for sensing lateral departures of said element from said centered position and responsively generating signals representative of the direction and extent of said departures, and means coupled to said position sensing means in receiving relation to said signals for responsively generating magnetic compensating flux peripherally of said element productive of forces in opposition and proportional to the direction and extent of said departures represented by said signals, whereby said element is continuously restored to said centered position.

2. A stabilized magnetic levitation system according to claim **1**, further defined by said position sensnig means comprising first and second diametrically opposed pairs of light sources disposed in vertically spaced relation to a first face of said element to beam light adjacent the periphery of said element, said second pair of light sources circumferentially spaced 90° from said first pair of light sources, and first and second diametrically opposed pairs of light sensors disposed in vertically spaced relation to a second face of said element opposite said first face in corresponding vertical alignment with said first and second pairs of light sources to receive the light beamed therefrom, and sensors generating electrical signals proportional to the light received from said sources, whereby the algebraic differences respectively between the signals from said first pair of sensors and the signals from said second pair of sensors are representative of the direction and extent of departures of said element from said centered position.

3. A stabilized magnetic levitation system according to claim **1**, further defined by the compensating flux generating means comprising a first pair of diametrically opposed arcuate conductors each extending substantially 180° coaxially disposed with respect to said magnetic levitation field in outwardly spaced circumscribing relation to said element, a second pair of diametrically opposed arcuate conductors each extending substantially 180° coaxially disposed with respect to said magnetic levitation field in outwardly spaced circumscribing relation to said element at positions circumferentially spaced from said first pair of conductors by 90°, and servo means coupled to said position sensing means for driving currents through said first and second pairs of conductors with magnitudes and directions in accordance with said signals to thereby generate said magnetic compensating flux.

4. A stabilized magnetic leviiation system according to claim **2**, further defined by the compensating flux generating means comprising first and second pairs of diametrically opposed arcuate conductors each extending substantially 180° coaxially disposed with respect to said magnetic levitation field in outwardly spaced circumscribing relation to said element, said second pair of conductors circumferentially spaced from said first pair of conductors by 90°, first servo means coupled to said first pair of sensors for comparing the signals therefrom and developing a first position signal proportional to the algebraic difference therebetween, and second servo means coupled to said second pair of sensors for comparing the signals therefrom and developing a second position signal proportional to the algebraic difference therebetween, said first and second position signals being thereby representative of the direction and extent of departures of said element from said centered position, said first and second servo means respectively coupled to said first and second pairs of conductors to drive currents therethrough in accordance with said first and second position signals and thereby generate said magnetic compensating flux.

5. A stabilized magnetic levitation system according to claim **4**, further defined by said first servo means including a first bipolar difference amplifier having input terminals connected to said first pair of sensors and an output terminal, said amplifier generating said first position signal at the output terminal thereof, and a first controlled voltage supply having an input terminal and a pair of sets of output terminals; said supply generating voltages at said sets of output terminals in accordance with a signal at said input terminal thereof, said output terminal of said difference amplifier connected to said input terminal of said supply, said pair of sets of output terminals of said supply respectively connected to opposite ends of said first pair of conductors, said second servo means including a second bipolar difference amplifier having input terminals connected to said second pair of sensors and an output terminal, said second amplifier generating said second position signal at the output terminal thereof, and a second controlled voltage supply having an input terminal and a pair of sets of output terminals, said second supply generating voltages at said sets of output terminals thereof in accordance with a signal at said input terminal thereof, said output terminal of said second amplifier connected to said input terminal of said second supply, said pair of sets of output terminals of said second supply respectively connected to opposite ends of said second pair of conductors.

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