ABSTRACT OF THE DISCLOSURE

A system for stabilizing a magnetic element, such 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 the case of both the levitation and the levitating fields, the lines of flux from the north pole to the south pole are in a symmetrical disposition.

The present invention relates to a 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.

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 a manner productive of force opposing 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 the 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. However, 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 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 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 disc, 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 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 preferably spaced light source 20 at the beam to beam light towards a plurality of cells, or equivalent light sensors 19, 21, 22, and 23 disposed in vertically spaced relation to the disc in corresponding alignment with the light sources. The light sources and sensors are equal radially spaced outwardly from the arc 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 light sources 17 and 18. However, when the disc slips laterally from its centered position, a sensor of at least one of the diametrically opposed sensors 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 thus be appreciated that the direction and magnitude of lateral displacement of the disc is indicated by the extent 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. 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. 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 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°, co-axially disposed with respect to pole pieces 12 and 13 in outwardly spaced circumferential relation to disc 11. Also included is a second pair of opposed arcuate conductors 27 and 28, each extending substantially 180°, co-axially disposed with respect to the pole pieces in outwardly spaced circumferential 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. The flow of current in the conductors is controlled to oppose the specific field flux induced thereby.

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 oppositely disposed 22 and 23, 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 oppose the magnetic flux of 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 the centered position to wall the terminals 31 and 32.

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 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 positive polarity at terminal 33 and a negative polarity at terminals 31 and 32 and are respectively connected to sensors 19 and 21, whereas a negative signal having a magnitude proportional to the difference between the sensor signals is produced in response thereto. The output is amplified and is produced 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 respect to 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, comprising the difference amplifiers 38, is mounted illustratively in the path having a 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 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 maximum light from source 14 while source 16 is thereby reduced. By virtue of the difference between the signals applied to the input terminals of servo 29, the servo effects a compensating flux to create a counterclockwise current flow through conductor 24 and proportional counterclockwise current flow through conductor 26, as depicted by the dots in FIG. 3. Clockwise compensating flux Bc is thus generated concentrically about the conductors to interact and the compensating flux Bc, being directed clockwise, acts 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 Bc 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 a compensating flux to create a clockwise current flow through conductor 24 and proportional clockwise current flow through conductor 26, as depicted by the dots in the figure. As a result, counterclockwise compensating flux Bc, being directed counterclockwise about the conductors and interacting 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 through both sets of conductors 24, 26 and 27, 28 having appropriate magnitudes and directions to stabilize the disc 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 loops from 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 responsive 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 responsive generating magnetic compensating flux peripherally of said element, said compensating flux comprising 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 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-
responding 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 levitation 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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