MEANS FOR AND METHOD OF MOVING OBJECTS BY FERROHYDRODYNAMICS

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Fig 1

Fig 2

Fig 3

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MEANS FOR AND METHOD OF MOVING OBJECTS BY FERROHYDRODYNAMICS

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ABSTRACT OF THE DISCLOSURE

This application relates generally to means for and method of moving an object by induction and, more particularly, it covers a technique and structure whereby objects submerged in colloid-like fluids are moved by external forces setting up a change in the pressure distribution of the fluid. More specifically, a ferrohydrodynamic phenomenon is described whereby an object which is normally unaffected by the presence of a magnetic or an electric field may be moved by such a field.

Ferrohydrodynamics describes the static and dynamic processes associated with the motion and pressure distribution induced in incompressible, magnetically or electrically polarizable fluids when in the presence of an appropriate field gradient. The production of ferromagnetic fluids, for example, by a grinding technique in which ferromagnetic particles are colloidally dispersed in a carrier fluid has been described and the fluid properties characterized elsewhere. (Rosenweig, R. E., Nestor, J. W., and Timmins, R. S., "Ferrohydrodynamic Fluids for Direct Conversion of Heat Energy," Joint A.I. Ch. E./Institute of Chemical Engineers Meeting, London, June 1965.) Additional studies have developed a general fluid mechanical description of ferrohydrodynamic flows from the continuum point of view. (Neuringer, J. L., and Rosenweig, R. E., "Ferrohydrodynamics," Physics of Fluids vol. 7, No. 12, December 1964, 1927—1937.)

The terms ferromagnetic and ferroelectric materials shall apply to materials which become polarized in the presence of a magnetic and an electric field respectively. It has become customary to apply the terms ferromagnetic and ferroelectric to all such materials, whether or not such materials contain iron. This custom will be followed here.

Additionally, for the purpose of this discussion, ferromagnetic fluid and ferroelectric fluid shall be defined to mean a colloidal or colloid-like fluid comprising a carrier liquid in which extremely fine particles are suspended. A more detailed description of these fluids can be found in the papers cited above.

The purpose of this discussion is to describe a strikingly new technological force which is generated by electrical or magnetic fields on normally unresponsive objects. By way of example, the following discussion will be limited to discussing the development of a force on a nonmagnetic object when the nonmagnetic object is immersed in a ferromagnetic fluid in the presence of a nonuniform magnetic field. By way of analogy, the results to be described may be duplicated by generating forces on objects that are normally not responsive to electric fields.

Classically, Earnshaw's theorem is a statement that an electrical charge subjected only to electrical forces cannot be in stable equilibrium. While it may also be impossible, by analogy, to create stable equilibrium on a magnetizable body by a magnetic field or a body which normally may be manipulated by an electric field, the present invention seemingly circumvents the classical Earnshaw theory, at least to the extent of demonstrating that bodies which are normally nonresponsive to electric or magnetic fields may be placed into a state of stable equilibrium under specific conditions.

It is an object of the invention to describe means for and a method of creating a new and novel technological force by external means applied on a body which is normally immune or unresponsive to said external means.

It is yet another object of the invention to describe means for and method of creating a change in the pressure distribution of a ferrohydrodynamic fluid in the presence of a field.

It is yet another object of the invention to produce a force directly on a nonferromagnetic or a nonferroelectric object by means of a magnetic field or an electric field respectively.

It is still another object of the invention to describe means for and method of creating a change in the pressure distribution of a ferrohydrodynamic fluid in the presence of a field.

It is yet another object of the invention to provide means for and a method of varying the buoyancy of an object in a ferrohydrodynamic fluid.

It is still another object of the invention to provide means for and a method of moving the position of a nonferromagnetic object immersed in a ferromagnetic fluid by a plurality of magnetic fields.

It is still another object of the invention to provide means for and method of producing a technological force on a body by means of a field whereby said technological force is a function of a number of variables, and further whereby said technological force may be used in constructing a plurality of sensors by controlling one or more of the aforementioned variables.

In accordance with the invention, an apparatus for selectively moving a means comprises a ferrohydrodynamic fluid containing particles. A field means for inducing nonuniform forces in said fluid is also provided. The apparatus includes means to be moved made from a material which is not polarizable by the field means. The means to be moved is immersed in the fluid and in the field.

Additionally, in accordance with the invention, a process for moving a means by a magnetic or an electric field comprises providing one of the aforementioned fields and placing a ferrohydrodynamic fluid containing particles which are polarizable by the field into the field. The means to be moved is placed in the fluid and in the field, the means to be moved being made from a nonpolarizable material. The means to be moved is subjected to a difference in field intensity across portions of its surface whereby it moves in a direction of lowest field intensity.

The novel features that are considered characteristic of the invention are set forth in the appended claims; the invention itself, however, both as to its organization and method of operation, together with additional objects and advantages thereof, will best be understood from the following description of a specific embodiment when read in conjunction with the accompanying drawings, in which:

FIGURE 1 is a schematic representation useful in describing the theory of operation of the present invention;
FIGURE 2 is a schematic representation of a means for moving or levitating a nonmagnetic object by means of a plurality of magnetic fields; and
FIGURE 3 is a schematic representation of an electrical switch embodying the principles of the present invention.

THEORY—FORCE ON A NONMAGNETIC BODY

Referring to FIGURE 1, consider a nonmagnetic body,
a sphere for example (although any arbitrary shape will do), having a volume $V$ and a surface area $A$ immersed in magnetizable (ferromagnetic) fluid (not shown). Let $z$ be a unit vector in the up direction of a gravitational field whose magnitude is $g$. The vector force $\mathbf{F}$ experienced by the body is given by the following integration of surface and volume forces.

$$F_z = -\int_A \mathbf{p} \mathbf{d}A - z \int_V \rho g \mathbf{d}V$$

(1)

The fluid pressure is denoted by $p$, $\rho$ is body density, and $A$ is the unit normal to any point on the surface $A$. The surface integral in Eq. 1 may be transformed according to the divergence theorem of Gauss to give

$$\int_A \mathbf{p} \mathbf{d}A = \int_V \nabla p \mathbf{d}V$$

(2)

from which it is seen that the essential problem is to evaluate the pressure gradient. An expression for the pressure gradient is given by the momentum equation for the polarizable fluid obtained previously which reduces in the case of static equilibrium to

$$\nabla p = -\rho g + \mu_0 M V H$$

(3)

where $M$ is magnetic moment per unit volume, $\mu_0$ is the permeability of free space, and $H$ is the magnitude of the field. Combination of the foregoing then gives

$$\mathbf{F} = \int_V (\rho - \rho^f) g \mathbf{d}V - \mu_0 \int_V M V H \mathbf{d}V$$

(4)

The first term leads to the usual Archimedes’ law of buoyancy since

$$\int_V (\rho - \rho^f) g \mathbf{d}V = (\rho - \rho^f) g V$$

(5)

for any volume $V$ provided the densities as well as the gravitational constant are uniform over the volume. In general, evaluation of the second term in Eq. 3 involves a difficult integration. However, as it stands, this term informs us there is no force of magnetic origin exerted on the object if the field $H$ is of constant magnitude since under these conditions $\nabla H = 0$. For cases when $\nabla H$ is sensibly constant over $V$, we may write

$$\mu_0 \int_V M V H \mathbf{d}V = \mu_0 \int_V (M) V \nabla H$$

(6)

where

$$(M) = \frac{1}{V} \int_V M \mathbf{d}V$$

is the volume averaged magnetization. Accordingly, Eq. 3 then becomes:

$$\mathbf{F} = (\rho - \rho^f) g V - \mu_0 (M) V \nabla H$$

(7)

This relationship predicts the phenomenon of ferrohydrodynamic levitation; since $\nabla H$ can be impressed upon the system in any desired direction, it becomes possible to overcome gravity by orienting $\nabla H$ along the direction of $z$.

The aforementioned concept of ferrohydrodynamic movement has been verified. Into a beaker containing a ferromagnetic fluid comprising a colloidal dispersion of ferrite particles in kerosene, the manufacture of such fluid described in the first paper cited above, there was immersed a half-inch diameter nylon sphere. The density of this sphere was somewhat greater than the density of the fluid. When a permanent magnet was brought to the outside bottom of the beaker, thus causing a non-uniform magnetic field to pass through the ferromagnetic fluid, the sphere rose to the surface of the fluid, thus overcoming the force of gravity. In a similar fashion, it was possible to move the nylon sphere horizontally by relocating the direction of the magnetic field.

The physical mechanism governing the movement of the sphere may be described as follows. Initially, the force applied to the system originates from the attraction of the magnetic field upon the particles suspended in the carrier fluid. The particles may be considered strongly bonded to the fluid such that there is no appreciable deviation in particle concentration even in the presence of the applied field. The particles then transmit the force to the body of the fluid with the result that, from a macroscopic point of view, a body force appears throughout the fluid. Thus, the ferromagnetic mixture may be considered homogeneous with regard to its behavior in the applied field.

Just as gravity will act upon every unit volume of a fluid in a container and create a distribution of hydrostatic pressure, so will a magnetic field act upon every unit volume of a magnetizable fluid and create a different distribution of static pressure in order to establish a balance of forces. The fluid pressure at any point in the fluid is free to push upon any surface with which it is brought into contact. In the example described of the levitated ball, the pressure on the bottom of the ball was made to exceed the pressure on the top surface and hence it rose.

As Equation 7 demonstrates, the nonferromagnetic body tends to move toward a region of minimum magnetic field. In certain field geometries, it is possible to provide a point of minimum field in whose vicinity the nonferromagnetic body may be held in stable equilibrium by three-dimensional restoring forces. Such an arrangement is claimed useful for accelerometer devices, bearings, and vibration damping of satellites. The necessary field is provided, for example, by opposed bar magnets or a Helmholtz pair with opposed currents.

It is found that the immersed body is repulsed by either pole of a magnet, and this is entirely consistent with the foregoing discussion which indicated that the magnitude of the applied field and not its direction was the governing property. The vector $\mathbf{F}$ in FIGURE 1 is pointed in the direction of the force which the body experiences and this direction is towards the region of lower field. A radial field such as would emanate from an isolated pole piece would also provide a force in the direction of lower absolute magnitude of field although the diagram would appear altered. (See FIGURE 3.)

FIGURE 2—EMBODIMENT

In the FIGURE 2 schematic representation, a nonferromagnetic object, a sphere 11 for example, is situated in the center of a composite magnetic field created by four symmetrically positioned electromagnets 21–24. The electromagnets 21–24 are polarized to produce a mutually repelling field as depicted in FIGURE 2. The composite field hereby designated 26 is typical of that which is generated by the disclosed configuration which implies that the magnitude of the applied field and not its direction was the governing property. The vector $\mathbf{F}$ in FIGURE 1 is pointed in the direction of the force which the body experiences and this direction is towards the region of lower field. A radial field such as would emanate from an isolated pole piece would also produce a force in the direction of lower absolute magnitude of field although the diagram would appear altered. (See FIGURE 3.)

Assuming that the operating parameters and the operating environments of the electromagnets 21–24 are identical, the forces created by each of the magnetic fields on the sphere by means of the ferrohydrodynamic effect will not give rise to net force on the sphere 11, provided it is centrally located; otherwise the sphere experiences a restoring force that maintains its central location. It is also quite obvious that by varying or a combination of the electromagnets 21–24, the sphere may be positioned anywhere within the container 27.

FIGURE 3 depicts another arrangement. In this case, nonferromagnetic fluid 32 and a nonferromagnetic immiscible fluid 33 are placed in a container 34. The fluid 33 conducts electricity and may, for example, be mercury. A pair of normally open switch contacts 35 project...
through the top of the container 34. A single magnet 36 imparts a magnetic field through the fluids 32 and 33. The concentric dash lines represent lines of equal magnitude of magnetic field intensity and, as will be expected, the magnitude of magnetic field intensity is higher close to the magnet than in a remote position.

The FIGURE 3 configuration is obviously a switch actuating means. In the presence of the magnetic field 37, the electrically conducting fluid 33 rises, due to the ferrohydrodynamic levitation. Upon reaching the surface as shown in FIGURE 3, the electrically conducting fluid 33 shorts the contacts 35. In the absence of the magnetic field, the electrically conducting fluid 33 rests on the bottom of the container 34 as shown by line 37.

Furthermore, the notion of a switch is to be interpreted more broadly to include devices for switching not only current electric circuits but also thermal, material, optical, ultrasonic and all other possible fluxes of matter and energy. For example, an optical switch results if the non-magnetic body is transparent to the radiation to be transmitted while the magnetizable fluid is opaque to the same radiation. Then in place of electrical contacts 35 there may be substituted windows to achieve this object and hence yield a device that may be regarded as a shutter.

Additionally, assuming the nonmagnetic fluid of FIGURE 3 was a cylindrical body and graduated along its length, it is quite obvious that the exposed graduations would provide an indication of the strength of the magnet 36. From Equation 7, the levitating force on the cylinder would be related directly to magnetic field intensity. As the levitating force increases, that portion of the cylinder exposed above the fluid level would increase.

Referring to Equation 7, which is repeated here for clarity,

\[
\mathbf{F} = (\rho' - \rho) g V^2 - \mu_0 (M) \nabla \times \mathbf{H}
\]

it is noted that the equation is a relationship between seven scalar quantities and, separately, it represents a relationship between three directional quantities. The seven scalar quantities are \(\mathbf{F}, \rho, \rho', \sigma, \mathbf{V}, \mathbf{M}\) and \(\nabla \mathbf{H}\), whereas the three directional quantities are the direction of \(\mathbf{F}\), direction of \(\mathbf{z}\) and direction of \(\nabla \mathbf{H}\). Among the seven scalar quantities it is possible to regard any one as an input variable whose magnitude may be detected by adjusting the magnitude of any one of the remaining six scalar quantities. From this, it follows there are \(7 \times 6 = 42\) separate classes of devices which are inherently described by the equation. In addition, due to the directional quantities, there are \(3 \times 2 = 6\) more classes of devices, so in total \(42 + 6 = 48\) classes of devices are possible. Representative types of ferrohydrodynamic sensors are suggested below.

Variable: Device

\(\mathbf{F}\) \(\quad\) \(\text{Accelerometer, measures magnitude of acceleration.}\)
\(\rho\) \(\quad\) \(\text{Densitometer.}\)
\(\rho'\) \(\quad\) \(\text{Densitometer.}\)
\(\sigma\) \(\quad\) \(\text{Gravimeter.}\)
\(\mathbf{V}\) \(\quad\) \(\text{Volume measuring device.}\)
\(\mathbf{M}\) \(\quad\) \(\text{Magnetization measuring device.}\)
\(\nabla \mathbf{H}\) \(\quad\) \(\text{Device to measure magnetic field gradient.}\)

Direction

(a) Device to measure direction of acceleration.
(b) Device to measure direction of magnetic field gradient.

It is quite clear that the equations governing ferrohydrodynamic movement do not limit such movement to static effects. Time-varying fields will produce time-varying movement.

The various features and advantages of the invention are thought to be clear from the foregoing description.

Various other features and advantages not specifically enumerated will undoubtedly occur to those versed in the art, as likewise will many variations and modifications of the preferred embodiment illustrated, all of which may be achieved without departing from the spirit and scope of the invention as defined by the following claims.

What is claimed is:
1. A process for moving a means by a magnetic or an electric field comprising:
   (a) providing one of the aforementioned fields;
   (b) placing a ferrohydrodynamic fluid containing particles which are polarizable by said field into said field;
   (c) placing means to be moved in said fluid and in said field, said means being of a nonpolarizable material; and
   (d) subjecting said means to a difference in field intensity.
2. A process as described in claim 1 in which said field is a magnetic field and said particles are of magnetically polarizable material.
3. A process as described in claim 1 in which said field is an electric field and said particles are of electrically polarizable material.
4. A process as described in claim 1 in which said means to be moved is a solid object.
5. A process as described in claim 1 in which said means to be moved is a fluid which is immiscible in said ferrohydrodynamic fluid.
6. A process for manipulating a nonferromagnetic means by a magnetic field comprising:
   (a) providing a magnetic field;
   (b) immersing a nonmagnetic means in said magnetic field; and
   (c) passing a nonuniform magnetic field through said magnetic field and through said nonmagnetic means.
7. A process as described in claim 6 in which the force generated by said magnetic field on said nonmagnetic means is a function of \(\mu_0 <\mathbf{M}> \nabla \mathbf{H}\), where \(\mu_0\) is the permeability of free space, \(\mathbf{M}\) is magnetic moment per unit volume, \(\mathbf{H}\) is the magnitude of the field and \(\mathbf{V}\) is volume.
8. A process for manipulating a nonferroelectric means by an electric field comprising:
   (a) providing a ferroelectric field;
   (b) immersing a nonferroelectric means in said ferroelectric field; and
   (c) passing a nonuniform electric field through said ferroelectric fluid and through said nonferroelectric means.
9. A process as described in claim 1 where the field intensity decreases in the direction of selected movement.
10. A process as described in claim 6 where the magnetic field intensity decreases in the direction of selected movement.
11. A process as described in claim 8 in which the electric field intensity decreases in the direction of selected movement.
12. A process for moving a means immersed in a fluid comprising:
   (a) providing a fluid containing a dispersion of particles;
   (b) immersing a means to be moved in said fluid; and
   (c) inducing nonuniform forces on said particles adjacent to said means to be moved.
13. A process as described in claim 12 in which said last-mentioned means comprises an electric field and said particles comprise ferroelectric particles.
14. A process as described in claim 12 in which said last-mentioned means comprises a magnetic field and said particles comprise ferromagnetic particles.
15. A process as described in claim 12 in which said last-mentioned means induces a nonuniform field decreasing in the direction of selected movement.
16. Apparatus for selectively moving a means comprising:
(a) a ferrohydrodynamic fluid containing particles;
(b) field means for inducing nonuniform forces in said particles; and
(c) means to be moved made from a material which is not polarizable by said field means immersed in said fluid and in said field.
17. Apparatus as described in claim 16 in which said ferrohydrodynamic fluid is ferromagnetic, and said field is magnetic.
18. Apparatus as described in claim 16 in which said ferrohydrodynamic fluid is ferroelectric and said field is electric.
19. Apparatus as described in claim 16 in which said field intensity decreases in the direction of selected movement.
20. Apparatus as described in claim 16 in which said means to be moved is a liquid which is immiscible in said ferromagnetic fluid.
21. A levitation apparatus comprising the apparatus described in claim 16 in which said nonuniform forces decrease in a vertical upward direction.
22. A sensor comprising:
(a) a magnetic fluid;
(b) a nonmagnetic means immersed in said fluid;
(c) a nonuniform magnetic field passing through said magnetic means whereby a force as a function of the variables \( p, \rho', \gamma, \dot{z}, V, \mu_0, \langle M \rangle \), \( \nabla \times H \) is generated on said nonmagnetic means where \( \rho \) is the density of the nonmagnetic means, \( \rho' \) is the density of the magnetic fluid, \( g \) is the acceleration of gravity, \( \dot{z} \) is the unit vector in the up direction of a gravitational field whose magnitude is \( g \), \( V \) is volume, \( \mu_0 \) is the permeability of free space, \( M \) is magnetic moment per unit volume and \( H \) is the magnitude of the field;
(d) means for varying one of the variables in said force equation; and
(e) means for sensing the change of position of said nonmagnetic means in response to said change in variable.
23. An accelerometer comprising said sensor of claim 22 in which said variable is the force \( F \) where \( F \) is the vector force experienced by a body.
24. A densitometer comprising the sensor described in claim 22 in which said variable is \( \rho \) and/or \( \rho' \).
25. A gravimeter comprising the sensor described in claim 22 in which said variable is the gravity \( g \).
26. A magnetization measuring device comprising said sensor of claim 22 in which said variable is \( \langle M \rangle \).
27. A device to measure magnetic field gradients comprising said sensor of claim 22 in which said variable is \( \nabla \times H \).
28. Apparatus for controlling the movement of a means comprising:
(a) ferrohydrodynamic fluid containing particles;
(b) at least two spaced, mutually repelling fields passing through said ferrohydrodynamic fluid for polarizing said particles;
(c) a nonpolarizable means immersed in said ferrohydrodynamic fluid in normal equilibrium and between said fields; and
(d) means for varying the intensity of at least one of said fields.
29. An apparatus as described in claim 28 in which said fluid is ferromagnetic and said fields are magnetic.
30. Apparatus as described in claim 28 in which said fluid is ferroelectric and said fields are electric fields.
31. An apparatus as described in claim 28 in which said mutually repelling fields are identical and placed symmetrically about a point in said ferrohydrodynamic fluid.

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