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Electric and Magnetic Separation via Contactless Suspension of Particles, Droplets, and Bubbles

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Abstract

Contactless suspensions of particles, droplets, or bubbles by electric and magnetic fields are used for solid–liquid, solid–solid, liquid–liquid, and gas–liquid separations. Dielectric levitation and magnetohydrostatic separation techniques are two examples. The theoretical relationship existing between these techniques and the methods employed for free levitation of solid objects in vacuum and in midair are examined. Practical systems related to the latter methods as well as systems associated with magnetic and electric separation methods are reviewed.

1. INTRODUCTION

Magnetic and electric levitation methods for rocks, minerals, ceramics, plastics, and other materials in a gravitational field by a static and an alternating field are well known and documented in the literature (*1, 2*). These methods usually involve a sort of flotation of the particles in dielectric,

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magnetic, or other liquids, and thus permit separation of particles with different physical characteristics. Another type of levitation which is usually not regarded as related to the previous one is dealt with when a free suspension (without supplying any material support) of objects is sought (*3*). One of the unexpected outcomes of this paper is that the two modes of suspension are shown to be related to one another. The latter type of suspension is usually entitled by the term "levitation by fields." Strictly speaking, this type of levitation involves the attainment of stable equilibrium of a body by the action of forces generated by various kinds of fields, and it does not include (unlike the previous methods) partial support of a body by physical contact (*4*). The phenomenon related to this type of levitation has fascinated scientists through the ages, and it has attracted considerable attention in recent times as a means of eliminating friction or physical contact.

Although both methods of levitation involve the same rules when considered from a field theory viewpoint, there nevertheless exist many practical differences between the methods. The problems of static stability, for example, are similar in both cases. Dynamic stability, however, is made simpler when the first methods are considered. This is due to the physical contact with a surrounding liquid, which introduces viscous damping. Another example of a practical difference between the methods is due to the possibility of free suspension via a feedback system. This possibility is practical only for the latter type of levitation. It cannot be used for the first type since the introduction of a position sensor (which is needed in such systems and which is relatively large) will not differentiate between the many small particles involved in a separation task. The main similarity between the methods concerned is that in both of them we do not permit permanent contact between the suspended objects and solid structures in the field or on the field boundaries. The suspended objects are, therefore, supported in both cases mainly by the action of electric or magnetic fields or their combinations, which act against the gravitational field. Separation systems, however (which are related in the present classification to the first group of methods), are sometimes realized to operate as if they were two dimensional. Perpendicular cuts along one of the horizontal axes of the system will then show the same profile repeating itself. It is usual then to treat the system both technically and also theoretically merely in two dimensions. A two-dimensional solution of the field problem will yield an approximately correct answer in this case because the end effects can usually be neglected without much loss of precision. The particles separated in the realized systems are prevented in such cases from a weak tendency to move along the third axis by adding perpendicular walls to the system. The particles can then be regarded as fully suspended in two dimensions.

2. GENERAL BACKGROUND

The state of equilibrium is stable, unstable, or neutral depending, respectively, on whether the object, if slightly displaced from a position of equilibrium, would tend to return to the position of equilibrium, would tend to move further away from it, or would not tend to move at all. The object is in equilibrium when the resultant of the forces acting on it is zero.

For a small object the two conditions necessary for stable equilibrium to occur at a point (x_0, y_0, z_0) in a static field of force $F(x, y, z)$ are (5)

$$F(x_0, y_0, z_0) = 0 \qquad \text{and} \qquad \nabla \cdot F_{(x_0, y_0, z_0)} < 0 \tag{1}$$

The first is a condition of equilibrium and the second is a condition of stability. If F is an irrotational field (F is usually an irrotational field, since it is generated either by static electric sources or by magnetic sources which are outside the region of suspended objects. The superimposed gravitational field is also irrotational), we obtain

$$F(x, y, z) = -\nabla \Psi(x, y, z) \tag{2}$$

where Ψ is a potential energy function. (If we dealt, for example, with a small electrically charged object, Ψ would be the electric field potential multiplied by the size of the charge.) In terms of Ψ, the necessary conditions for stable equilibrium are (5)

$$\nabla \Psi_{(x_0, y_0, z_0)} = 0 \qquad \text{and} \qquad \nabla^2 \Psi_{(x_0, y_0, z_0)} > 0 \tag{3}$$

This condition guarantees that the oject will encounter a restoring force if it moves in any direction away from the equilibrium point (x_0, y_0, z_0). The difficulty in fulfilling these conditions in certain practical systems is discussed later when we describe related devices. Several practical methods, however, have been suggested to avoid the difficulty by creating situations which are not governed by the previous theory. An intriguing possibility is to use oscillating (nonstatic) field sources. Some of these systems are similar to those obtained by static sources (*3, 6*). The alternating field there (*3, 6*) merely affects the behavior of average forces in a way that assists in fulfilling conditions (for the average oscillatory forces) which are similar to those of Eqs. (3). Another method of stability by oscillation is achieved when the suspended object is the oscillatory member of an electromechanical system (*7*). The latter method is responsible for suspension in such widely different systems as dielectric levitation, MHS levitation, protons in alternating-gradient synchrotons, and magnet levitated in combined constant and alternating magnetic fields. The feature common to all these physical systems is that they can be described by the Mathieu differential equation (7). The question of how the parameters of such systems should be chosen to obtain a stable equilibrium can be answered with the aid of a stability diagram derived from the Mathieu equation (7). Instability in a given degree of freedom can sometimes be changed to stability by forcing certain conditions of oscillations on the suspended objects. The parameters describing these conditions are strict in defining exactly certain frequency, direction, and amplitude of oscillation.

3. ELECTRIC AND MAGNETIC LEVITATION

3.1 Electrostatic Levitation

In an electrostatic field, $E(x, y, z)$, outside the regions of sources, the following are obtained

$$\nabla \cdot E = 0, \qquad \nabla \times E = 0, \qquad \text{and} \qquad E = -\nabla \phi \tag{4}$$

where ϕ is the electrostatic potential. The force acting on small charged object, q, placed in the field is given by

$$F = qE \tag{5}$$

Taking the divergence of Eq. (5) and recalling the first of Eqs. (4), we see that

$$\nabla \cdot F = 0 \tag{6}$$

for all points in the charge-free region. Although Eq. (5) may satisfy the first of the two necessary conditions (see Eq. 1) for stable equilibrium, Eq. (6) violates the second. Therefore, the electrically charged object placed in an electrostatic field can be in a state of equilibrium but it cannot rest in a state of stable equilibrium under the influence of an electrical force alone [Earnshaw's theorem (5)]. Furthermore, Earnshaw's theory was developed further by Braunbeck and it governs systems which are more complicated than the small point charge (5). It is also impossible to suspend stable larger charged objects. Stable suspension is also impossible in situations where the charge is generated by charge movements in the originally neutral object as a

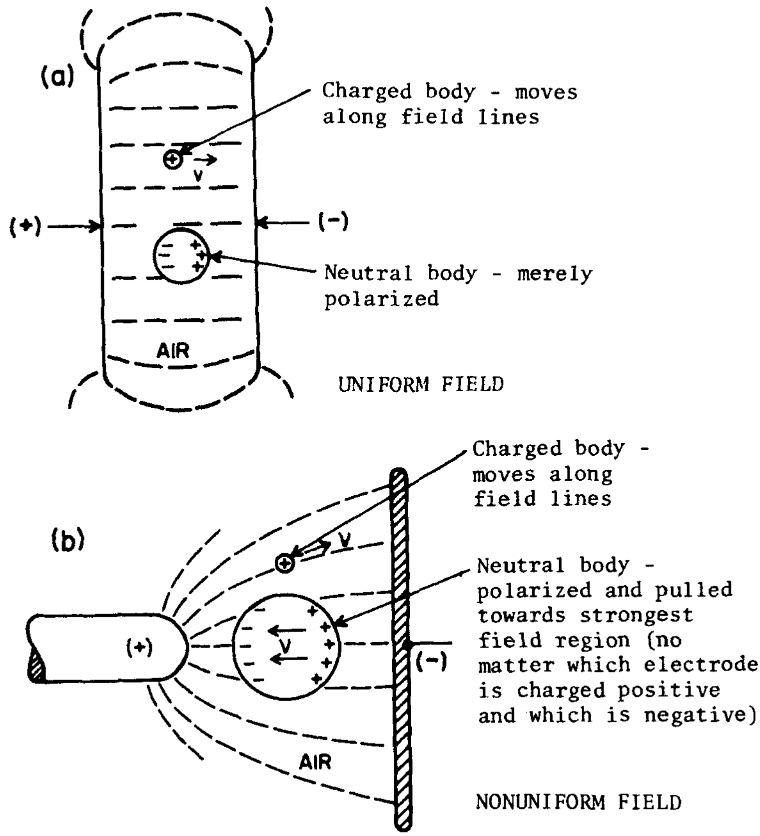

FIG. 1. Comparative behavior of neutral and charged bodies in (a) a uniform electric field and (b) a nonuniform electric field.

result of the influence of the field sources. The latter is valid when the object is in air or in vacuum. The situation may, however, change if the surrounding medium possesses a larger dielectric constant as explained in the next subsection.

3.2 Dielectric Levitation (DL)

The electric field, uniform or nonuniform, exerts a force upon a charged object (electrophoretic effect). It is characteristic of nonuniform fields, however, that they exert a "ponderomotive force" upon small neutral objects (see Figs. 1 and 2). Figure 1 compares schematically the behavior of neutral

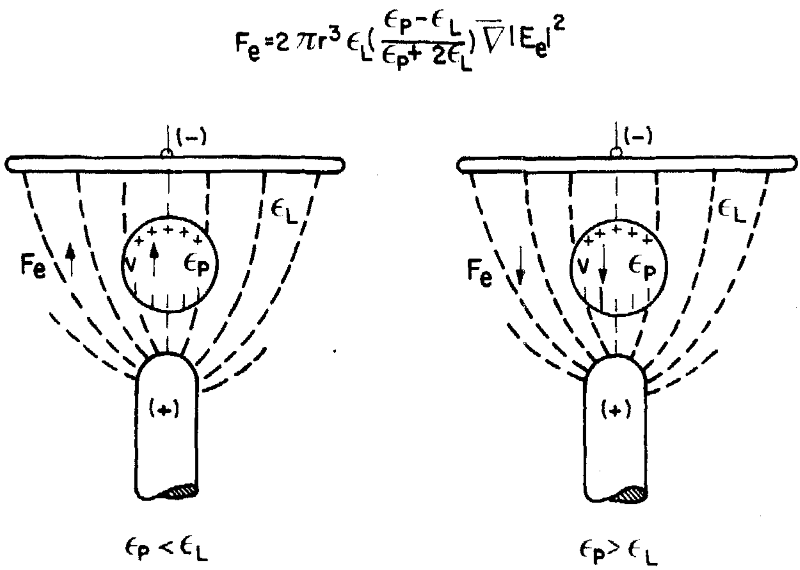

FIG. 2. Comparative behavior of different objects in a nonuniform electric field, immersed in insulating fluids, representing dielectric levitation.

and charged bodies in a uniform and a nonuniform static electric field in air. Figure 2 shows the case of dielectric levitation (DL).

The motion of neutral particles placed in a nonuniform electric field has been termed dielectrophoresis (*8*). Whether the particles, droplets, or bubbles move toward the regions of high field strength or away from these regions depends on the electrical properties of the objects as well as those of the surrounding medium [pure dielectric liquids such as transformer oil, benzene, toluene, kerosene, gasoline, corn oil, and carbon tetrachloride, or suspensions of fine ferroelectric particles (titanates such as $BaTio_3$ and $PbTio_3$) in nonpolar media].

It is well established that nonuniform electric fields can induce translational and rotational motions of neutral organic and inorganic bodies [solid particles, droplets (*9*), bubbles] in insulating fluids. They can be used either as a tool to effect separation (*10–14*) and filtration (*15–17*) of different kinds of particles or as a way to study the electrical properties of particular kinds of particles (*18, 19*).

The dielectrophoretic force acting on a small, nonconducting, polarized but uncharged object immersed in an insulating dielectric fluid and in a slightly nonuniform electric field has been shown to be given by (*20*)

$$F^e = \alpha V(E_0 \cdot \nabla)E_0 = \frac{1}{2}\alpha V \nabla (E_0^2) \tag{7}$$

where α is the polarizability, V is the volume of the object, and E_0 is the imposed external electric field. For various shapes α is given by

$$\alpha = 3\varepsilon_1(\varepsilon_2 - \varepsilon_1)/(\varepsilon_2 + 2\varepsilon_1) \tag{8a}$$

for spheres,

$$\alpha = 2\varepsilon_1(\varepsilon_2 - \varepsilon_1)/(\varepsilon_2 + \varepsilon_1) \tag{8b}$$

for long thin cylindrical rods, and

$$\alpha = \varepsilon_1(\varepsilon_2 - \varepsilon_1)/\varepsilon_2 \tag{8c}$$

for a thin plate.

Equations (8a)–(8c) are valid only for a dilute suspension (a case of many particles with relatively large distances between them in a liquid suspension). From Eqs. (7) and (8a), with $V = 4/3\pi r^3$, the translational force is given by

$$F^e = 2\pi r^3 \frac{\varepsilon_1(\varepsilon_2 - \varepsilon_1)}{\varepsilon_2 + 2\varepsilon_1} \nabla(E_0^2) \tag{9}$$

where r is the radius of the sphere, ε_1 and ε_2 are the absolute permittivities* of the surrounding nonconducting fluid and the object, respectively, and $\nabla(E_0^2)$ is the gradient that would be obtained at the specific location of the object if it were not there. F^e varies directly as E_0^2 and therefore is independent of the sign of the applied voltage (or electrode polarity).

In the special case of isodynamic separators (*8*), F^e is constant over the whole zone where the separation takes place. In the general case, F^e varies from location to location throughout the separation zone. The fluid dielectric medium must possess a combination of electrical and rheological characteristics that insure the performance of separation at a technologically acceptable rate. It is imperative that the liquid should have a minimal toxicity, high chemical and environmental persistance, low flammability, and be unreactive in respect of leaching ionic species from particles.

*The dielectric constant of a real material is a "constant of the material" only at a particular frequency and reflects the slope of the polarization versus field strength relation at that frequency.

In the ac case, E is taken to be the rms voltage, and the driving force varies as $2E^2 \cos^2 \omega t$, where ω is the angular frequency $2\pi f$ of the electric field. Hence, with ac, the observed effect can possess, in addition to a steady component which varies as E_0^2, an oscillating component which is also quadratic in E_0 and which has a period π/ω; as ω increases, the magnitude of the resulted oscillation of the object will decrease rapidly.

The difference between the object and medium permittivity, $\varepsilon_2 - \varepsilon_1$, determines both the force direction and magnitude. Therefore, when $\varepsilon_2 > \varepsilon_1$, the object will be attracted into regions of higher electric field intensity,* whereas when $\varepsilon_2 < \varepsilon_1$, the object will be attracted into regions of lower electric field intensity—the basic requirement in DL.

The dielectric levitation (buoyancy) force is given by

$$F_l^e = -|F^e| \tag{10}$$

therefore

$$F_l^e = 2\pi r^3 \frac{\varepsilon_1(\varepsilon_1 - \varepsilon_2)}{(\varepsilon_2 + 2\varepsilon_1)} \nabla(E_0^2) \tag{11}$$

It follows from this equation that the hovering position depends on (a) the ratio of the electrical characteristics of the material to be separated and that of the separating media, and (b) on the parameter, depending on the field intensity and field gradient.

Based on the expression given in Eq. (9), and referring to the case in which $\varepsilon_2 > \varepsilon_1$, we may conclude that the neutral object cannot be in stable equilibrium anywhere in the space-charge-free region of a static nonuniform electric field since the divergence of $\nabla(E_0^2)$ can nowhere be negative, and $\Delta\varepsilon > 0$. From Eq. (9) we see that $\nabla \cdot F^e$ cannot be negative for $\varepsilon_2 > \varepsilon_1$ objects. This is also the case for all dielectric objects suspended in air. On the other hand, an object which satisfies $\varepsilon_2 < \varepsilon_1$ (in Eq. 9) can be in stable static levitation equilibrium in space-charge-free dielectric field. Experimental results and examples discussing the above are given elsewhere (*21, 22*). Note that this theorem is not applicable in full to dynamically stabilized levitation schemes.

3.3 DL in Time-Dependent Electric Field

In the case of slightly conducting particles immersed in a conducting fluid, Eq. (9) becomes invalid. A new set of equations, when applying ac or dc

*The basic requirement in WHIES and HGES (*17, 21*).

electric fields in the presence of conducting objects and fluids, was developed to take advantage of the charge relaxation effect (*15, 16, 21*).

Benguigui and Lin arrived at a concise result for the time-average dielectrophoretic force due to an ac dielectric field acting on a spherical particle with conductivity σ_2 in a fluid of conductivity σ_1 (*21*)

$$F^e = 2\pi r^3 \varepsilon_1 \left[\frac{\varepsilon_2 - \varepsilon_1}{\varepsilon_2 + 2\varepsilon_1} + \frac{3(\varepsilon_1\sigma_2 - \varepsilon_2\sigma_1)}{\tau(\sigma_2 + 2\sigma_1)^2\,(1 + \omega^2\tau^2)}\right] \nabla E^2_{\text{rms}} \quad (11\text{a})$$

where ω is the angular frequency of the applied field, E_{rms} is the rms electric field magnitude, and

$$\tau = (\varepsilon_2 + 2\varepsilon_1)/(\sigma_2 + 2\sigma_1) \quad (11\text{b})$$

is a fundamental charge relaxation time. Equation (11a) predicts that the dielectrophoretic force is frequency dependent, and a map of the stable regimes of levitation has been provided by Jones et al. (*23*).

3.4 Magnetohydrostatic Levitation (MHSL)

The considerable analogy of electrohydrodynamics to the statics and dynamics of magnetic liquids has been shown to extend to the behavior of solids, droplets, and gas bubbles in para- and ferrofluids when subjected to nonuniform magnetic fields (*22, 24–27*). This method is known as "magnetohydrostatic fractionation" or "magnetogravimetric separation" and involves the transformation of magnetic forces into hydrostatic pressures to form a continuous density gradient column. Multifractionation (S–S or S–L separation or filtration) in a single operation is obtainable.

This application is directed to a MHS process for exciting a neutral object to achieve mobility for orientating, repositioning, and transporting objects and for separating objects by operation in the appropriate medium.

In the event the object being acted upon is suspended in a polarizable medium (paramagnetic aqueous solutions or ferrofluids), the net polarization of the whole may be such as to evoke a magnetic force in favor of pushing the body either into ($\chi_p > \chi_l$) or away ($\chi_p < \chi_l$) from the region of higher field intensity (positive or negative displacement).

The magnetic levitation force acting on a linear object immersed in a continuous phase (magnetic fluids) and in a slightly nonuniform magnetostatic field is given by

$$F_l^m = -|F^m| = -\frac{V}{2}(\chi_p - \chi_l)\nabla(H_0^2) \tag{12}$$

where χ_p and χ_l are the magnetic susceptibilities of the object and the surrounding fluid, respectively, H_0 is the imposed external nonuniform magnetic field, and $\nabla(H_0^2)$ is the gradient of the squared field intensity that should be obtained at the location of the objects if the objects were not there. The value of $\nabla(H_0^2)$ and the nonuniformity of the H-field is highly dependent on the geometry (configuration and shapes) of the poles that establish the field. F^m can be controlled by the geometry and intensity of the field and by $\Delta\chi$, but it becomes zero when a body is suspended in a medium of equivalent magnetic susceptibility.

Note that in the case of isometric field conditions, the magnetic force is constant along a radial direction. In other words, the magnitude of the magnetic force is independent of the position, so that all particles present are subject to identical forces, no matter what their positions in the electrode confines.

The gravitational net force on a sphere of radius r and mass density ρ_2 immersed in a magnetic fluid of density ρ_1 is given by

$$F^G = \frac{4}{3}\pi r^3(\rho_2 - \rho_1)\mathbf{g} \tag{13}$$

where $\mathbf{g}$ is the acceleration due to gravity. Setting this force equal to the vertical MHS levitation force given by Eq. (12) gives,

$$\frac{1}{2}(\chi_p - \chi_l)\nabla(H_0^2) = (\rho_2 - \rho_1)\mathbf{g} \tag{14}$$

Thus over a limited range of distances from the suspended particle, a statically stable force–distance characteristic can be obtained. Equation (14) is usefully applied for small objects in static equilibrium in a MHS axisymmetric levitation unit.

In the case of MHSL, although the divergence of $\nabla(H_0^2)$ can nowhere be negative, the quantity ($\Delta\chi = \chi_p - \chi_l$) can be negative or positive. Therefore, stable equilibrium is possible for $\Delta\chi < 0$, but not for $\Delta\chi > 0$.

Note that in wet-high-intensity magnetic separation (WHIMS), high-gradient magnetic separation (HGMS), and magnetic filtration (MF), the value of $\chi_p - \chi_l > 0$ (for trapped particles), and therefore a stable equilibrium is not obtained. Technically, however, the particles are in contact with solid objects and are kept stable as a result of this contact. In MHS systems

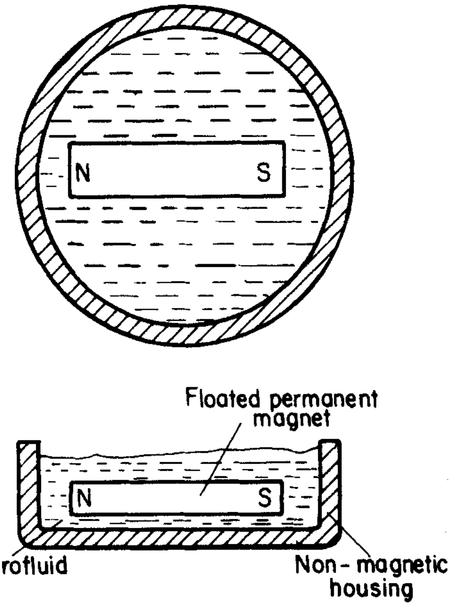

FIG. 3. Suspension of a permanent magnet immersed in a ferrofluid.

containing dia- and paramagnetic particles (all with $\chi_p < \chi_l$), stable equilibrium is obtainable in the gravitational field by static and alternating magnetic fields, and this has been confirmed experimentally for six degrees of freedom; the three translations along the x-, y-, and z-axes, and the three rotations about these axes.

Suspension of a permanent magnet immersed in a ferrofluid is shown in Fig. 3. The magnetostatic condition here is similar to the electrostatic condition in Fig. 2, (left-hand side). There exist, however, two main differences: (a) the source of the nonuniform field in the electrostatic case is external to the floating object, while the source of the field in the second case is the object itself, (b) the μ of the present object can be regarded as being smaller than that of the environment (this in itself is similar to the relationship existing between the ε's in the previous electrostatic case, but we deal here with an equivalent μ which is due to the special position of the working point on the material demagnetization curve). This is due to the fact that homogeneously magnetized permanent magnets (especially magnets constructed of modern samarium-cobalt materials) can be shown to be equivalent to a layer of a nonmagnetic material possessing $\mu = 1$, which is sandwiched between two magnetically "charged" surfaces responsible for producing the magnetic field.

3.5 Free Levitation by Magnetic and Electric Fields

This type of levitation (or suspension) is usually entitled by simpler terms such as "magnetic suspension," "magnetic levitation," and "electric suspension" (*28*). The adjective "free," however, has been added in order to emphasize that levitation is attained merely by the action of fields without any material contact to surrounding objects. A surrounding liquid is also precluded by definition, and suspension of the latter type should be possible for objects in vacuum as well. It appears obvious that this type of suspension, besides representing a fascinating phenomenon, should possess technological and scientific applications. We shall mention some of them: Frictionless bearings to replace mechanical bearings (*29*) in situations where a very high rotational speed is needed [in ultracentrifuges (*30*) and in special gyroscopes (*31*)] and also in optical measurements where a rotating mirror at a very high velocity is applied (*30*). It is also advantageous for experiments in generating gravitational waves by rotating a special mass at a very large speed (*30*). A relatively recent application is in building freely levitated high-speed trains which do not employ wheels (*32*). A suspension of a model in wind tunnels without employing strings, wires, and other mechanical connections is of advantage, since the connections, if they existed, would tend to interfere with the flow of gas in the tunnel (*33*).

Several methods have been realized for the free suspension of objects by fields. The immediately simpler methods are related directly to the theoretical background in Sections 3.1 and 3.2. It has been shown there that a stable suspension of objects may be achieved if the characteristic constant of the environment (ε or μ) is larger than that of the suspended object. This condition does not permit levitation in electrostatic fields, since there is no material in existence where the dielectric constant is smaller than that of free space (a free suspension of objects is realized by its definition in vacuum or in air). The magnetic counterpart is nevertheless possible, since there exist materials (diamagnetic materials) whose permeability is smaller than that of free space. The application of diamagnetism is, however, limited to the suspension of relatively small weights (*4, 22*). This limitation arises from the fact that in diamagnetic materials the relative permeability is never much less than unity. The diamagnetic effect is, therefore, very small. On the other hand, the relative permeability of superconductors is virtually zero, and therefore they are more useful for suspension (*4*). Levitation systems, utilizing superconductivity, usually involve complicated and expensive apparatus (*34*).

A well-known method of levitation is levitation by induction, where eddy currents are used for suspension (*35*). Although this method is not within the range of discussion given in the previous paragraph, its theory is somewhat

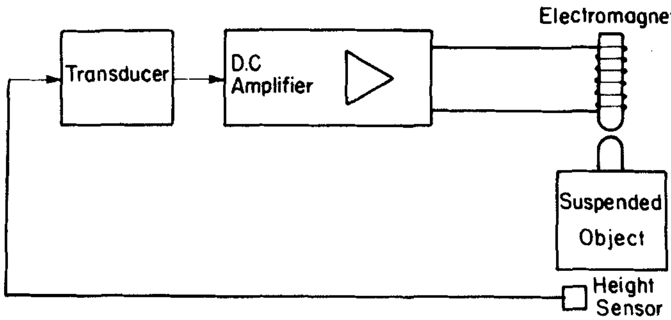

FIG. 4. Levitation by a servo control system.

similar to that of suspension by diamagnetic materials. A conductor in an alternating magnetic field reduces the effective field in its vicinity in a way similar to a diamagnetic material in a static magnetic field. This method of suspension has been investigated by Laithwaite (*35*). The theory involved in this type of suspension is somewhat related to that discussed in Section 3.3, although the conductivity of the suspended object is assumed here to be relatively large.

In another known method, suspension is achieved by using a feedback system (*4, 28–30, 32, 33*). The current of an electromagnet can be controlled in accordance with the position of a body suspended in its field. By the variation of the electromagnet current, the magnetic force acting on the body is made to behave like the restoring force of a spring. The sensing element consists in many cases of a photocell illuminated by a beam of light, which is partly intercepted by the body. Electrical sensors of inductive or capacitive type are also used. A block diagram of a feedback system for magnetic suspension is shown in Fig. 4. Due to the effect of the control, the electromagnet current increases rapidly when the object descends. Hence, a restoring force is created and the condition of the suspended object is similar to that of an object suspended from a spring.

In much of the literature on the subject of suspension by feedback, the levitating electromagnet is supplied by direct current, although alternating current has also been used. A method of electrostatic levitation can be realized with a conductive body suspended in an electric field of electrodes whose potential is controlled. The suspension methods discussed in the present paragraph are not related to the theoretical background in Sections 3.1, 3.2, and 3.4. The reason is that the previous theory has assumed stationary field sources, and the introduction of feedback violates this assumption. Another method of levitation enables a relatively simpler

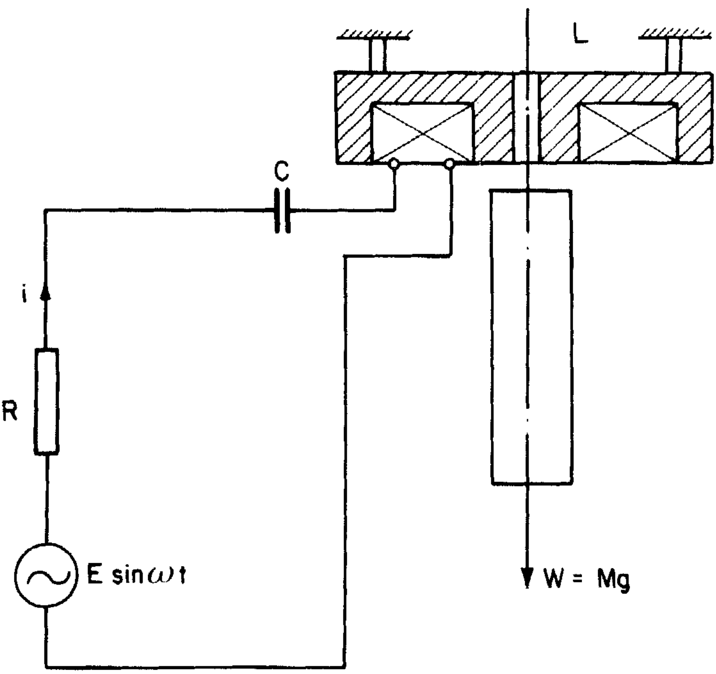

FIG. 5. A simple tuned circuit levitator.

control of the electromagnet current than the one attained when a feedback system is applied. This is achieved by constructing the suspension electromagnet in Fig. 5 as the inductive member of an LCR tuned circuit supplied by an appropriate alternating current source (*3, 6, 28, 31, 36, 37*). The resonance effect causes the electromagnet current to be sensitive to the position of the suspended object. The magnetic force acting on the suspended object by the electromagnet is made to behave as a restoring force. This is attained by an appropriate tuning of the resonant circuit with respect to the source frequency, and levitation becomes feasible.

4. CONCLUDING REMARKS

(1) In the case of DL, stable equilibrium of different uncharged objects such as gas bubbles, voids, liquid droplets, and solid particles with relatively lower permittivity ($\varepsilon_2 < \varepsilon_1$) in strongly nonuniform static

electric fields is possible, while stable equilibrium of objects with relatively higher permittivity ($\varepsilon_2 > \varepsilon_1$) is impossible.

(2) In MHSL, stable equilibrium of gas bubbles, voids, droplets, and particles with $\chi_p < \chi_l$ in slightly nonuniform magnetostatic fields is possible, while stable equilibrium of particles with relatively higher magnetic susceptibility ($\chi_p > \chi_l$) is impossible.

(3) The above-mentioned conclusions are not applicable in full to dynamically stabilized levitation schemes involving feedback or parametric stabilization. The stabilizing influence of ac systems or of active feedback is made possible even in systems where the ε and μ relationships mentioned previously are not favorable and is mainly intended for the second class of suspension systems. It is employed for freely levitating objects in fields. A feedback levitator for example is not intended for the separation of particles (which is one of the applications of the first class). This is due to the introduction of a position sensor (which is needed in such systems and which is relatively large) that will not differentiate between the many small particles involved in a separation task.

(4) The enormous potential of free levitation by fields, dielectrophoretic-, and MHS-levitations is still to be realized. In the last few years, DL and MHSL have only begun to gain recognition by the technical community at large as viable technologies of significant potential. To forecast the development of MHSL and DL on a purely scientific level is rather difficult. However, both methods are highly interdisciplinary techniques and thus progress can be expected to occur at the interface between applied electromagnetism and other disciplines such as the theories of fluid dynamics, transport processes, electricity, surface sciences, and colloid chemistry.

(5) In conclusion, most of this paper is devoted to the theory that permits separation by suspension of materials and particles with the aid of magnetic and electric fields which are superimposed on the gravitational field. A relatively large part of the paper deals with the conditions for suspending particles stably in static fields. The stability of the suspended particles depends mainly on relationships that exist between the sizes of the environment electric and magnetic properties (ε and μ) and those of the particles materials. The employment of special suspension schemes (such as an ac suspension or an active feedback in the system) enables one to suspend solid objects stably and freely in vacuum and in mid air even if the basic relationships mentioned previously are not fulfilled. The latter special schemes possess many technological and scientific applications which are reviewed in this paper.

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