SPACE APPLICATIONS OF DIAMAGNETIC SUSPENSIONS

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ABSTRACT

Conventional noncontact magnetic suspensions require power and sensor feedback to maintain stability of the levitated object. Magnetic suspensions using superconductors require neither power nor feedback for stability but must be maintained at low temperatures. This paper discusses a little known type of magnetic bearing that does not require power, sensor feedback, or cooling: diamagnetic suspension. While the bearing pressure for diamagnetic suspensions is typically limited to 1 gram force per square centimeter, their simplicity, environmental tolerances, and wide range of material choices suggest that they may be useful for a number of space applications. This paper discusses the fundamentals of diamagnetic suspensions as well as their potential space applications.

INTRODUCTION

Diamagnetic suspensions or bearings can best be understood by comparing them to superconductor bearings. Superconductor bearings using the Meissner effect are well known in the literature. These bearings are noncontact, consume no power, do not require feedback for stability, and are essentially dragless. However, superconductor bearings do require cooling, and the need for cooling increases cost and complexity, and lowers reliability for the system as a whole.

By contrast, diamagnetic bearings using ordinary, room–temperature materials are much less well known. Like superconductor bearings, diamagnetic bearings rely on the diamagnetic properties of materials subject to magnetic fields. Diamagnetic bearings are also noncontact, consume no power, do not require feedback, and are essentially dragless.

Compared to superconductor bearings, diamagnetic bearings have one significant disadvantage and two significant advantages. The disadvantage is that the bearing pressures for diamagnetic bearings are significantly less than those for superconductor bearings. The advantages are that diamagnetic bearings do not require cooling, and that the range of usable diamagnetic materials is huge compared to the limited number of superconducting materials available.

This paper discusses potential space applications that can make use of the advantages of diamagnetic suspensions. The basic equations of diamagnetic suspensions are discussed first, followed by discussions of specific potential applications.

BASIC EQUATIONS OF DIAMAGNETIC SUSPENSIONS

Equation 1 below gives the basic equation for diamagnetic suspensions [ref. 1]. In Equation 1, H is the magnetic field, χ is the volume magnetic susceptibility of the diamagnetic material, **F** is the force, and the integral is taken over the volume of the material. The gradient, **grad**, is taken with respect to the position of the diamagnetic body. All quantities are in centimeter–gram–second (cgs) units. We also assume that the diamagnetic material is isotropic and that χ is uniform in the diamagnetic body. The force **F** can be used to levitate a diamagnetic body. Alternatively, the diamagnetic material may be fixed, and the force can be used to levitate a magnet.

$$\mathbf{F} = (1/2)\ \mathbf{grad} \int \chi H^2\ dV \tag{1}$$

In general, the magnetic field H is produced by the diamagnetic material itself, just as it is produced by nearby free currents, ferromagnetic materials, permanent magnets, and so forth. However, the magnitude of the volume magnetic susceptibility is normally much less than $1/4\pi$. For example, using bismuth, $\chi = -1.2 \times 10^{-5}$ cgs units. In this case, the magnetic fields are only slightly different from what they would be if the diamagnetic material were not present. Thus, a good first-order approximation is to calculate the magnetic field H without the diamagnetic material, and use this calculated field in Equation 1 to approximate the force.

Equation 1 can be used to estimate the magnitude of diamagnetic pressures. Consider the force in the z-direction, F_z. It is straightforward to show, using Equation 1, that

$$F_z = (1/2)\chi \int \left[d(H^2)/dz\right] dz\ \ dx\ \ dy = (1/2)\chi \int H^2\ \ dx\ \ dy \tag{2}$$

$$F_z = (1/2)\chi \int H^2\ \mathbf{k} \cdot \mathbf{dS} \tag{3}$$

where dV from Equation 1 has been replaced by dz dx dy in Equation 2, and the second integral in Equation 2 is over the surface of the diamagnetic body. Equation 3 follows from Equation 2, in that dx dy = $\mathbf{k} \cdot \mathbf{dS}$, where **k** is the unit vector in the z direction and **dS** is a vector surface element oriented outward from the diamagnetic body.

Figure 1 shows the simple case of a thin rod of cross-sectional area A oriented parallel to z and subject to a field H on one end. For this case, Equation 3 reduces to

$$F_z = (1/2)\ \chi\ A\ H^2 \tag{4}$$

The *bearing pressure* exerted on the rod, P, is just Fz divided by A, or

$$P = (1/2)\ \chi\ H^2 \tag{5}$$

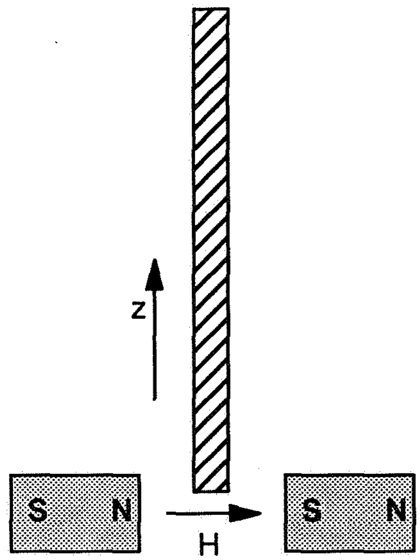


Figure 1. Rod Exposed to a Magnetic Field on One End

Although Equation 4 was derived for the special situation of a thin rod with one end in a magnetic field, this equation is generally useful for estimating the magnitude of diamagnetic bearing pressures. Very good neodymium-iron rare earth magnets generate fields up to about H = 12,500 oersted. Using this value of H and the susceptibility of bismuth in Equation 5 gives a bearing pressure of roughly 1000 dynes/cm^2, or about 1 gram force per square centimeter.

Various magnetic field geometries and better diamagnetic materials, such as pyrolytic graphite, can be used to increase the bearing pressure. On the other hand, practical constraints often reduce the achievable bearing pressure. Nonetheless, 1 gram/cm^2 is a convenient bearing-pressure estimate for evaluating the basic feasibility of diamagnetic suspensions.

It should be emphasized that magnetic field limits restrict the maximum bearing pressure, but not the total force or the force-to-mass ratio of the bearing. The total force supported by diamagnetic suspension can be increased by increasing the area. The force-to-mass ratio can be increased by simultaneously reducing the thickness of the levitated object and the scale length of the magnetic field.

The methodology for evaluating diamagnetic suspensions with respect to a potential application is summarized as follows. A bearing pressure of 1 gram/cm^2 is used as a general estimate for determining the basic feasibility of diamagnetic suspensions for the application. If the application places significant restrictions on the magnetic fields or the diamagnetic materials, e.g., an application to levitate weakly diamagnetic silicon wafers, then Equation 5 should be used directly to estimate bearing pressure. If the potential application appears feasible using the general estimate, the next step is to design the diamagnetic suspension itself. Details of the diamagnetic suspension design will depend on the given application and its constraints. Once a design is established, the next step is to calculate or estimate the magnetic field H without the diamagnetic material present. Next, this approximate H is used in equations such as

Equation 3 to calculate the components of force on the diamagnetic body. Lastly, bearing stability and rigidity can be determined by considering small displacements from the assumed equilibrium position.

SPACE APPLICATIONS

It was mentioned in the introduction to this paper that diamagnetic suspensions have relatively low bearing pressures, but do not require cooling and work with a wide range of materials. These general characteristics of diamagnetic bearings will be discussed briefly with reference to space applications. Specific applications will be discussed following the general comments.

The use of bearings in space includes a number of applications with low bearing pressures. In some cases, such as containerless material processing, a low bearing pressure is related to the microgravity environment. In other cases, such as for sensors, low bearing pressure applications in space stem from the need for miniaturization and/or enhanced performance.

The lack of a need for cooling or power means that diamagnetic bearings are intrinsically very reliable, compared to other noncontact bearings. High reliability is a major asset for space applications. In fact, one potential application is to use diamagnetic bearings to provide highly reliable passive bearings to back up primary, active magnetic bearings.

The ability of diamagnetic suspensions to work with a wide variety of materials is attractive for suspensions where the material is fixed by nonbearing constraints. An example of a nonbearing constraint would be a materials–processing application that must process a given material or class of materials.

The following sections describe specific space applications where the use of diamagnetic suspensions may be advantageous.

Material Processing

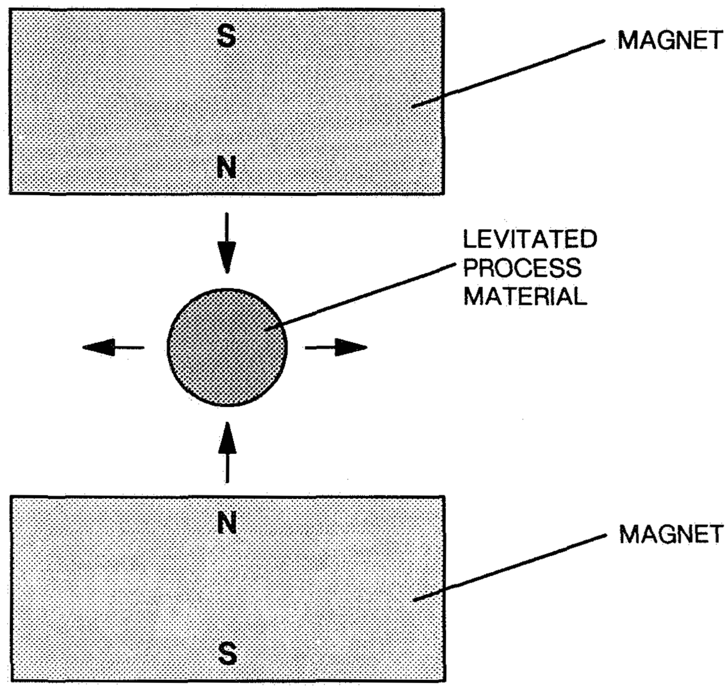
Diamagnetic suspensions may be used for containerless material processing in space. This is a good application for diamagnetic suspensions, since space–based processing is done in a microgravity environment and low bearing pressure is not an issue. Additionally, diamagnetic suspensions function in vacuum, unlike acoustic levitations.

Figure 2 illustrates a simple magnet geometry for confining a diamagnetic material. Note that the magnetic field at the point midway between the magnets is zero by symmetry. Since diamagnetic materials are repelled by magnetic fields, the midway point is a stable equilibrium. This geometry is similar to that used for ferrofluid suspensions of inert objects.

The concept of using diamagnetic suspensions for materials processing is useful only if the range of materials that can be suspended is large. Fortunately, this is the case. Diamagnetic materials form one of the broadest classes of material and include metals, ceramics, the three major semiconductors (silicon, germanium, gallium arsenide), glasses, plastics, almost all organic matter, and water.

As a concrete example, consider suspending silicon. We will assume that the spacecraft may be subject to DC acceleration, a, as large as 10^{-4} g = 0.1 cm/s^2 during material processing [ref. 2]. To determine the basic feasibility of the concept, we need to estimate the maximum size of a silicon object that can be supported. Suppose the typical thickness of the silicon in the direction of acceleration is L and its density (d) is 2.33 g/cm^3. Acceleration of the spacecraft causes a pressure, P_{Si}, exerted on the surface perpendicular to the thickness L given by

$$P_{Si} = L \; d \; a = 0.233 \; (g/s^2cm^2) \; L \tag{6}$$



Note: The arrows indicate the direction of magnetic fields.

Figure 2. Simple Configuration for Levitating a Diamagnetic Material

The susceptibility of silicon is roughly $\chi = -0.3 \times 10^{-6}$ cgs units. For comparison, this is about 1/40th the susceptibility of bismuth and about half that of water. We will also assume that our magnetic fields are restricted by practical design constraints to half the maximum value for rare earth magnets, or about 6250 oersted. Equation 5 then gives the estimated bearing pressure as about 6 dynes/cm^2. Using Equation 6 we then get an estimate for L as

$$6 \; dynes/cm^2 = 0.233 \; (g/s^2cm^2) \; L$$
$$L = 26 \; cm \tag{7}$$

This is a large thickness of silicon, and it indicates the basic feasibility of diamagnetic suspensions for this material in space.

A valid question is whether high temperatures or phase transitions will destroy the diamagnetism. This issue needs to be addressed with respect to specific materials. However, many materials for which data is available are diamagnetic through their melting temperature. Examples include bismuth, germanium, gold, sodium chloride, and water [ref. 3].

Finally, it should be mentioned that diamagnetic suspensions using a wide variety of materials have already been demonstrated on earth. Levitation of graphite and bismuth were originally used in diamagnetic suspensions. Ponizovskii [ref. 4] gives a good survey of this earlier work. More recently, Beaugnon and Tournier [ref. 5] report levitating water, wood, ethanol, and acetone, using superconducting magnets.

Sensor Applications

The earliest applications of diamagnetic suspensions were for sensors [ref. 4]. These sensors were constructed for earth-based operations, but the technology involved is well-suited for space applications.

The early work in diamagnetic sensors demonstrated high sensitivities. Two examples will indicate the sensitivities available. A tiltmeter for measuring tilting of the earth's crust caused by tidal forces was constructed by Simon et al. [ref. 6]. Sensitivity was on the order of 24 nanoradians. Ponizovskii [ref. 4] discusses a rotating mass for measuring low pressures using drag forces. The smallest measurable pressure for the device was 10^{-10} torr.

The basic idea behind diamagnetic sensors is to levitate an inertial, or proof, mass and measure its response to accelerations, rotations, magnetic fields, and so forth. A variety of signal pickup methods, such as optical, capacitive, or magnetic methods, may be used to measure the response of the proof mass. The undisturbed state of the proof mass may be stationary relative to sensor fixture. Alternatively, the undisturbed state may be rotating, as in a gyro application, or it may be oscillating.

The low gravity of space opens up additional possibilities for diamagnetic sensors. For example, one possibility is to levitate a magnet using the diamagnetic properties of a silicon chip. Such sensors would integrate the proof mass directly with the signal processing electronics. As a result, this type of sensor has the potential advantages of compactness, low cost, and high reliability. Such sensors could be used as accelerometers, gyroscopes, pressure gauges, magnetic field sensors, and the like. Levitation of magnets on earth using silicon and external, supporting magnetic fields was demonstrated by Pelrine [ref. 7].

To estimate the feasibility of silicon diamagnetic sensors, recall from Equation 7 that diamagnetic bearing pressures for silicon were estimated at roughly 6 dynes/cm^2. We will assume the thickness of the levitated magnet is 100 microns at a density of 7.4 g/cm^3, a number that can be achieved by grinding neodymium-iron magnet material. The diamagnetic pressure will support a magnet of this thickness up to a maximum acceleration, a, given by

$$a = (6 \ \text{dynes/cm}^2)/(0.01 \ \text{cm} \times 7.4 \ \text{g/cm}^3) = 81 \ \text{cm/s}^2 = 0.08 \ \text{g} \qquad (8)$$

This magnitude of acceleration may be useful for monitoring and/or controlling oscillations in large space structures or microgravity experiments. Of course, the maximum allowable acceleration can be increased using highly diamagnetic films deposited on silicon, or by reducing the magnet thickness. Amorphous silicon, obtained by ion bombardment of crystalline silicon, also has a significantly larger diamagnetic susceptibility.

Lastly, an attractive area for diamagnetic suspensions is in compact, sensitive inertial navigation devices. Diamagnetic accelerometers have been investigated in the past [ref. 8], but more work appears to be needed to determine the limits of the technology.

Rotating Rings

Rotating rings or flywheels have been suggested for use as energy storage devices or for stabilizing large space structures [ref. 9]. Diamagnetic bearings may offer advantages for these types of devices.

Research is only at the basic idea stage in this area. However, since diamagnetic bearings will function without power or cooling, they are a reliable means of supporting high speed rotations. A rotating ring might be supported totally by diamagnetic bearings. Another option is to incorporate diamagnetic bearings as backups for the primary ring bearings. Still another possibility suggested by Pelrine [ref. 7] is to use diamagnetic bearings to support low–speed, start–up rotations. Induced–current magnetic bearings would then be used at higher speeds where they become effective.

Diamagnetic bearings are simple components and can be made very small. This suggests the possibility of replacing single large rotating rings with many small rings in a distributed approach. Multiple rings would have an advantage in terms of redundancy.

Another issue is the need for safety. Multiple rings may increase the possibility of a single ring failing. On the other hand, confinement of a breaking ring is easier when the rings are smaller. Normally, rotating rings require confinement structures, in case a ring breaks apart at high velocities. The confinement structure, however, adds unwanted mass to the system. For small rings, it may be possible to utilize the existing space structure as the confinement structure. A small ring breakup would then cause some local damage, but would not actually penetrate the structure. The tradeoffs between the savings in mass and the risk of local damage are unknown at present.

The feasibility of diamagnetically supported rotating rings depends on the specific mission. In general, if only low accelerations are expected, diamagnetic bearings are attractive, since the bearing pressures will be low. The reverse is true for space missions involving high accelerations of rotating rings.

SUMMARY

Diamagnetic suspensions offer unique capabilities for space applications. They are frictionless, need no power or cooling, can be made very small, and function using a wide range of materials. Their only significant limitation is their relatively low bearing pressure. Typically, diamagnetic bearings are useful when bearing pressures are on the order of 1 gram force per centimeter squared or less.

A number of space applications have been identified as candidates for diamagnetic suspensions. These include containerless material processing, sensors, and bearings for high–speed rotating rings.

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