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Magnetic Bearings

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ABSTRACT

Methods of freely, magnetically, suspending rotors in air, in various media, and in a vacuum are described. Rotors weighing from 10^{-6} lb to over 100 lb have been suspended and spun, but both larger and smaller rotors can be employed. Rotor speeds in excess of 10^{6} rps and centrifugal fields of over 10^{9} g have been obtained. When "coasting" freely in air at a pressure of 10^{-9} torr, $\dot{f}/f \sim 10^{-9}$ sec^{-1}, were $\dot{f}$ is the loss in rotor speed per second at a speed "f." A double magnetic suspension also will be described.

IDEAL BEARINGS for high speed rotors should have at least the following characteristics:

1. The rotor should be able "to seek its own axis of rotation" in order to avoid precise balancing problems. At the same time the bearings should accurately hold the rotor at a desired predetermined position.
2. The bearings should be free of friction and require no lubricants. Also, they should be able to support the rotor in air in any medium or inside a completely sealed vacuum chamber.
3. The bearings should be free of wear and thus have infinite life.
4. They should be able to support rotors of any desired size, shape, or weight. Also, long shafts should not be necessary.
5. The bearings should be able to damp the rotor effectively when it is disturbed or when it encounters a critical vibration frequency.
6. The overall power required to operate the bearings should not be excessive.

It is, of course, obvious that the above conditions cannot be satisfied completely, but characteristics of the magnetic bearings to be described in this paper roughly approximate most of them.

If rotors weighing in the order of 100 lb or more are spun to near their bursting point around a vertical axis, the oil thrust bearings in general use not only consume excessive power, but often have a comparatively short life. Furthermore, they generate heat in such quantities that certain experiments are difficult to carry out.

BASIC ARRANGEMENT

However, the foregoing problems often can be solved (1)* by a simple arrangement illustrated by Fig. 1. The rotor R is supported by a thin flexible shaft, S, which passes through the journal bearing, B, and is fastened to a solid steel cylinder, C, which also is the armature of an induction motor. Practically all the weight of the rotating parts is supported by the attraction between the magnets A and C, which have a small clearance.

For heavier rotors, an electromagnet is used, and for lighter ones, a permanent magnet is employed. The slight excess weight is taken by the small thrust bearing, T, which served to stablize the system. It will be noted that the magnetic flux through C does not change when it rotates. As a result, there is no electromagnetic drag. It was found experimentally that the friction due to the magnetic support was itself extremely minute.

TYPICAL MAGNETIC SUSPENSION

The question arises as to whether or not the thrust bearing, T, the journal bearing B, the cylinder C, and the shaft S can be completely removed. This was accomplished in our laboratory at the University of Virginia in 1937 and has been greatly improved since that time (2).

Fig. 2 shows a schematic diagram of a typical magnetic suspension; Fig. 3 is a photograph of a suspended 2 in. steel sphere; and Fig. 4 is a photograph of suspended ultracentrifuge rotor. Both are shown freely suspended in air.

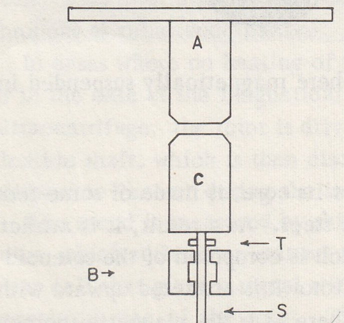

Fig. 1 - Schematic diagram of partially magnetically suspended rotor

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*Numbers in parentheses designate References at end of paper.

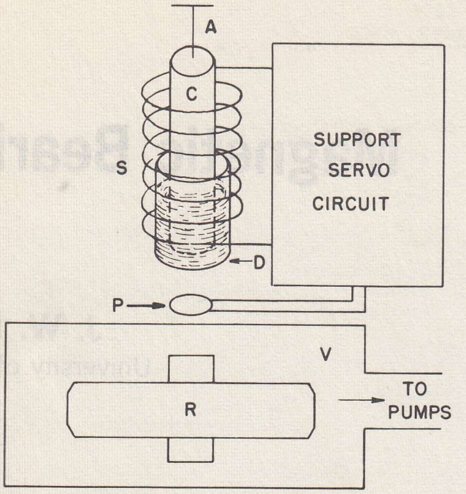

Fig. 2 - Schematic diagram of method of magnetically suspending rotors freely in a vacuum

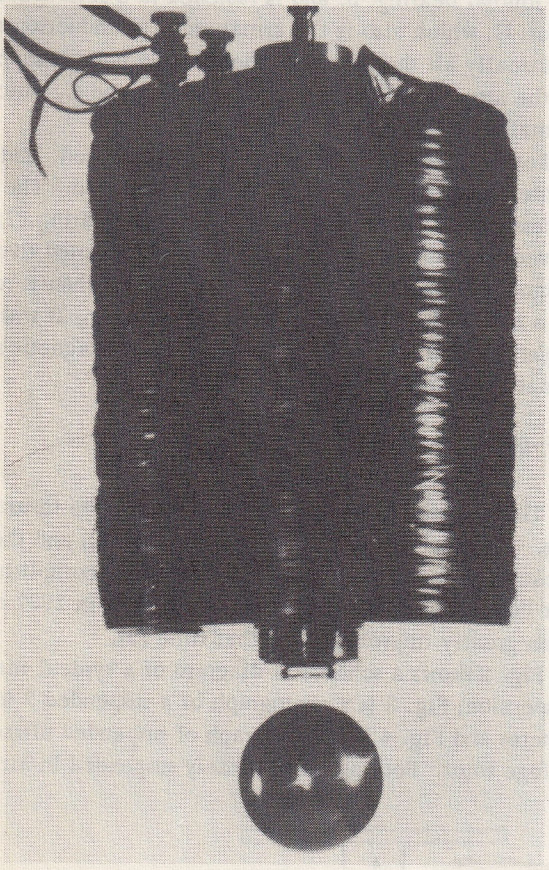

Fig. 3 - Two inch steel sphere magnetically suspended in air

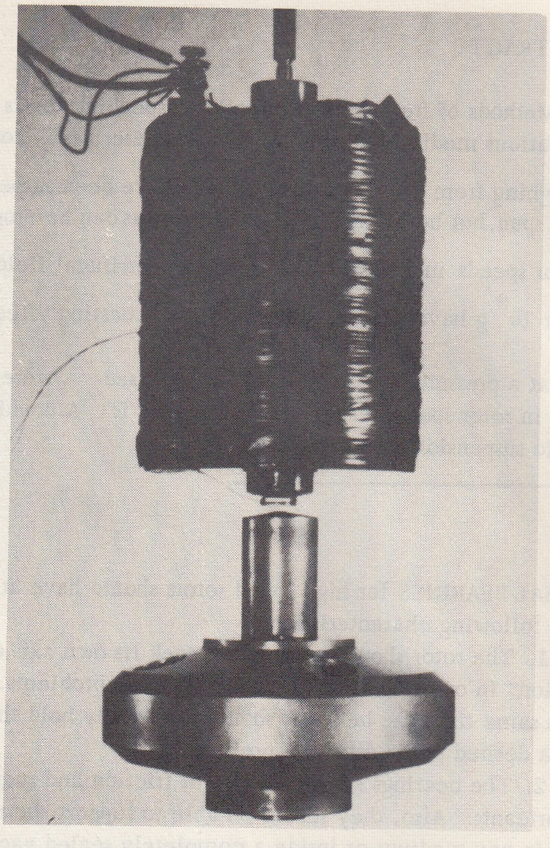

Fig. 4 - Thirty pound steel ultracentrifuge rotor magnetically suspended in air

In Fig. 2, the rotor R, or its core, is made of some ferromagnetic material such as steel. As a result, it is attracted by the electromagnet, which is composed of the solenoid S and the iron core C. The rotor R is attracted upward with a force $F = M (\partial H/\partial z)$, where M is the magnetic moment of the rotor and $\partial H/\partial z$ is the vertical gradient of the magnetic field H. Consequently, it will "fly up" to the electromagnet unless the current through the solenoid S is properly regulated. This is accomplished automatically by the servo support circuit and the sensing coil P.

If the rotor moves upward, the change in impedance of the coil P causes the servo circuit to decrease the current through the solenoid S. If the rotor moves downward, the system increases the current through S. Derivatives of the signal in the circuit prevent oscillations. If properly adjusted, this type of servo circuit will hold the rotor very precisely at the desired vertical position.

It will be observed that the axial magnetic field of the electromagnet is diverging downward and that the maximum field is on the axis. Consequently, the rotor will seek a position of stable equilibrium on the axis. If the rotor receives a horizontal disturbance, the lower end of the core C, which hangs as a pendulum from the support A, is dragged along with it through the dashpot of oil, D. This effectively damps all horizontal motion.

In practice, it is found that no vertical or horizontal motion of the rotor can be observed with a microscope focused on the rotor surface. Careful measurements with an interferometer have shown that when the circuits are properly adjusted, any vertical oscillation of the rotor has an amplitude of less than the wavelength of light, or 5×10^{-5} cm. This should be expected from theory, and in fact the noise in this bearing probably can be made to approach the natural fluctuations of the system.

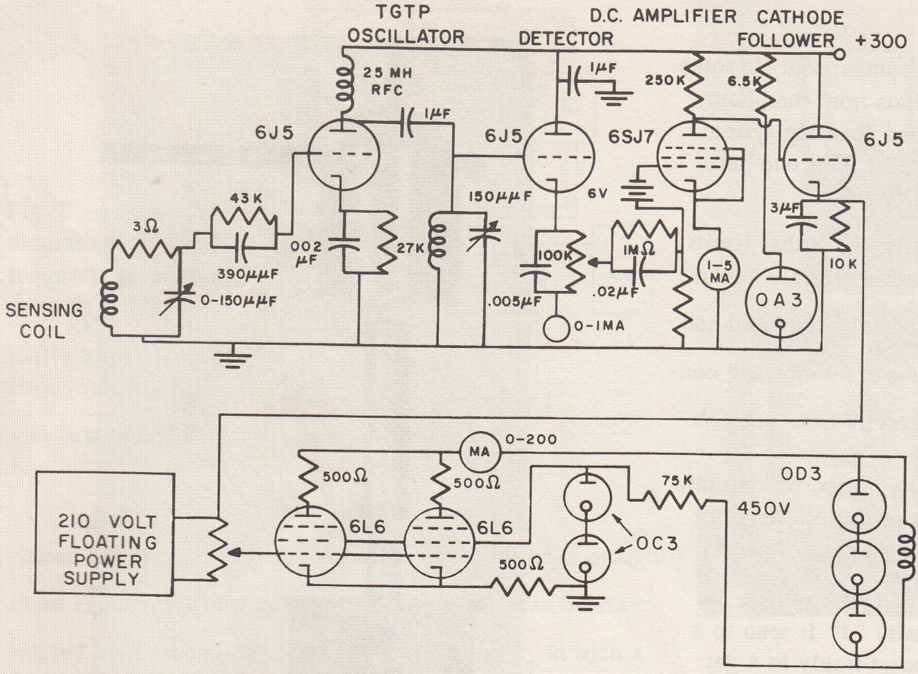

Fig. 5 - A servo controlled magnetic suspension circuit

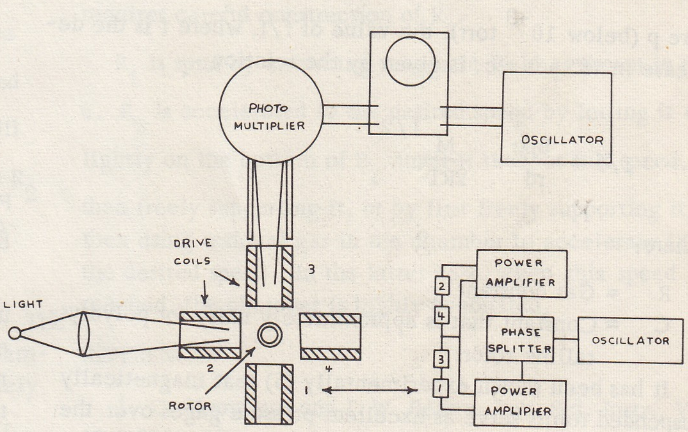

Fig. 6 - Schematic diagram of a method of driving the rotor and of measuring its speed of rotation

SERVO CIRCUIT

Fig. 5 shows a schematic diagram of a typical servo circuit. The sensing coil is in the grid circuit of a tuned grid, tuned plate oscillator, which usually has a frequency of several megacycles per second. When the rotor moves with respect to the core, the amplitude and frequency of this oscillator change. This signal is next rectified and differentiated.

Both the signal and its derivative are amplified and made to actuate the power tubes, which supply the current for the support solenoid. Although this is a nonlinear circuit, its performance can be qualitatively understood by the much simpler linear theory that can be found in the textbooks on circuit analyses (3). However, the more exact theory should be used for more quantitative approximations.

Many types of servo circuits and sensing devices may be used. In many cases, it is more convenient to use a light-beam photoelectric or a capacitor sensor instead of the coil (2).

ROTOR SPEED

Fig. 6 shows a schematic diagram of a convenient method of spinning the rotor, where small changes in temperature of the rotor are not important. It will be observed that the rotor serves as the armature of an induction motor, the rotating magnetic field of which is produced by the four field coils. The rotor also may be used as the armature of a synchronous or reluctance motor.

In cases where no heating of the rotor can be tolerated, as in the case of the magnetically supported equilibrium ultracentrifuge, the rotor is driven to full speed by a long flexible shaft, which is then disconnected and the rotor is allowed to "coast" during the sedimentation (4).

The speed is measured by shining a beam of light on the rotor, which reflects or scatters the light into a photomultiplier cell that gives a signal with a frequency equal to the repetition rate of the rotor. The signal from this cell is amplified and put on one pair of plates of an oscilloscope. A signal from a known frequency oscillator is placed on the other oscilloscope plates for frequency comparison. In some cases, it is convenient to count the signals from the photomultiplier cell directly with a high speed counting system. The rotor speed is routinely measured to at least one part in 10^6.

With the above types of drive the only factor that limits the rotor speed is the strength of the rotor material. Rotors with weights of $100\text{-}10^{-6}$ lb have been freely supported and spun successfully. Rotor speeds in excess of 10^6 rps and centrifugal fields of well over 10^9 times gravity have been obtained.

It has been found that with properly constructed systems, the friction of the magnetic bearing is negligible in comparison to the air or gaseous friction on the rotor down to pressures of between $10^{-7}\text{-}10^{-8}$ torr. If, for example, a spherical rotor of radius "r" and density "d" is spun to a speed of "f" rps and then allowed to coast freely in a gas of molecular weight M at absolute temperature T and pressure p (below 10^{-3} torr), the value of f/f, where f is the decrease in "f" per sec, is given by the relation

$$f/f = \frac{5pc}{rd} \left(\frac{M}{2RT}\right)^{1/2}$$

where:

R = Gas constant
C = Constant that is approximately unity for polycrystalline rotors

It has been shown experimentally (5) that magnetically suspended rotors serve as excellent pressure gages over the range from 10^{-4} to 5×10^{-8} torr. The magnetically suspended ultracentrifuge rotor shown in Fig. 4, when coasting freely at 600 rps inside a vacuum chamber where the air pressure is the order of 10^{-7} torr, loses only about 1 rps per day.

ROTOR DAMPING

Fig. 7 shows a convenient way of spinning a rod or tubular type rotor, or in cases where it is necessary, of damping the rotor at both ends. The strong permanent magnet supports the rotor and the servo controlled solenoid keeps the rotor stabilized. The dashpot of oil shown surrounding the upper magnet damps the upper end of the rotor while a similar device surrounding the core of the solenoid damps the lower end. With this arrangement, it is very simple to spin a rotor up to its first critical vibration frequency.

Unless the rotor is well balanced, trouble is often encountered in passing the criticals with tubular and rod type rotors. However, when not in the criticals, the rotation is extremely smooth. It is obvious that the upper permanent magnet may be replaced by a solenoid. Also, this arrangement can be used to support rotors that spin about a horizontal axis. However, in the latter case, the ends of the long rotor should be made of ferrite, or other low-loss ferromagnetic material, to reduce frictional losses due to electromagnetic drag. Also, the dampers must be modified. Three dimensional magmetic bearings also have been devised by H. M. Parker and his collaborators (6) at Virginia, but so far have been used only under special conditions.

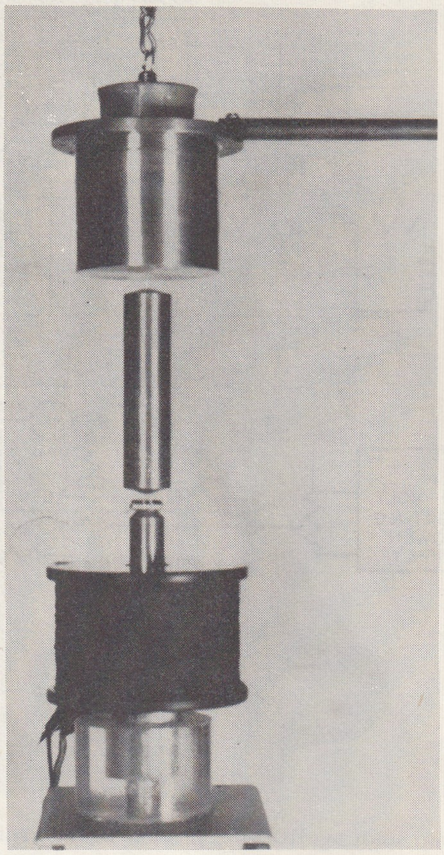

Fig. 7 - Method of spinning rotors whose length is much greater than their diameters

STABILIZATION

It has been found experimentally that by reducing the residual gas pressure surrounding the rotor by freezing it out with liquid helium, and by taking sufficient care in shielding of stray magnetic fields with Permalloy sheets, as well as using damping mechanical vibrations, etc., $\dot{f}/f \sim 10^{-9}$ sec^{-1}, where $\dot{f}$ is the change in the rotor speed "f" while the rotor is coasting (4). This bearing friction evidently is due to the drag produced by the residual gases surrounding the rotor and to the friction of the magnetic bearing itself.

Fig. 8 shows a schematic diagram of a double magnetic suspension that reduces the preceding two factors to extremely small values (7). The upper rotor R_1 is magnetically suspended by the solenoid S_1. R_1 is vertically stabilized by the servo circuit E_1. If a second ferromagnetic rotor R_2 is

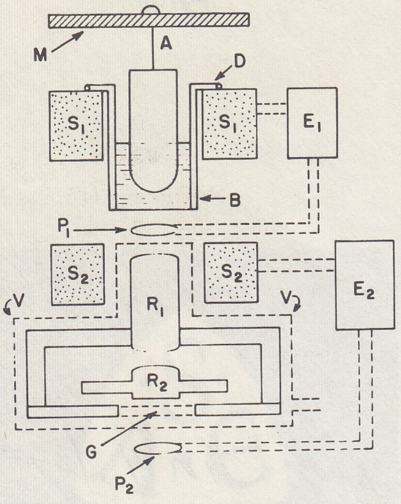

Fig. 8 - Schematic diagram of double magnetic suspension; rotor R_2 is magnetically suspended from rotor R_1; R_2 also is surrounded by R

placed below R_1, it will be attracted upward, and if brought close enough, will fly up to R_1. However, R_2 can be stabilized by a second solenoid, S_2, surrounding R_1 in such a way that R_1 essentially becomes the core of S_2.

The servo circuit E_2 and pick-up coil P_2 stabilize the vertical height of R_2 so that R_2 is magnetically supported from R_1, which in turn is magnetically supported. It will be noted that essentially all magnetic flux that supports R_2 originates from R_1. The "skirt" of rotor R_1 made of nonferromagnetic material surrounds R_2.

The dotted line in Fig. 8 is a nonconducting window. The dotted line V shows the location of the glass vacuum chamber. It is clear that if R_2 is made to spin at approximately the same speed as R_1 (within a few rps), the value of $\dot{f}/f$ for R_2 becomes extremely minute, since its magnetic support and the surrounding vacuum chamber are spinning at approximately (but not exactly) the same speed "f."

Fig. 9 shows a photograph of a double magnetic suspension with the vacuum chamber and skirts of R_1 removed. Also, R_1 is made longer than used in practice so that it will show in the photograph. It is found in practice that R_1 and R_2 can be made stable both vertically and horizontally. Both R_1 and R_2 are damped horizontally by the dashpot around the core of E_1. However, R_1 is more damped than R_2. This requires careful construction of R_2.

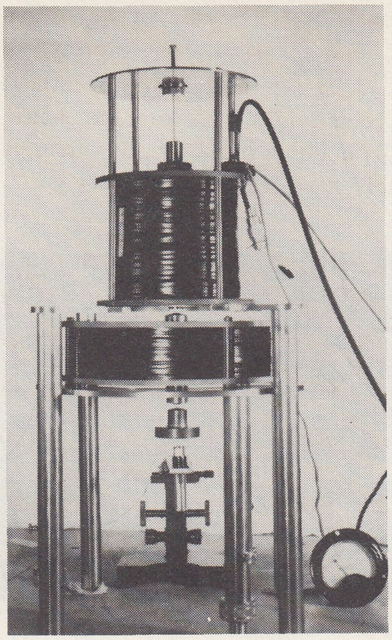

Fig. 9 - Photograph of double magnetic suspension; the upper rotor R_1 was made longer than the one in use so that it could be photographed at both ends; also, the skirt that surrounds the lower rotor R_2 and the vacuum chamber are not shown

R_1 is spun by a rotating magnetic field as shown in Fig. 6. R_2 is accelerated to the desired speed by letting it rest lightly on the bottom of R_1, until it reaches full speed, and then freely supporting it, or by first freely supporting it and then using residual gas in the chamber to accelerate it to the desired speed. In the latter case, when this speed is reached, the chamber is highly evacuated.

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