Arrangements and performance of

Magnetic Suspensions for High-Speed Rotors

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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" to avoid precise balancing problems. At the same time, the bearings should hold the rotor accurately at a desired 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 distributed or when it encounters a critical vibration frequency.
6. The over-all power required to operate the bearings should not be excessive.

Of course, all these conditions cannot be satisfied completely, but characteristics of the magnetic bearings described in this article come close.

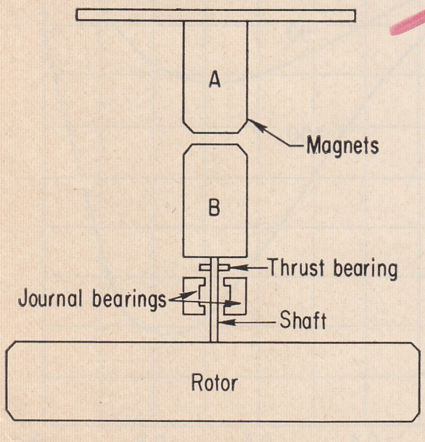

Fig. 1—Partially magnetically suspended rotor.

IF rotors weighing 100 lb or more are spun around a vertical axis to near their bursting point, conventional oil thrust bearings consume excessive power and have a short life. Furthermore, they generate so much heat that certain experiments are difficult to carry out.

However, these conditions can be remedied by a simple arrangement shown in Fig. 1. A rotor is supported by a thin flexible shaft which passes through the journal bearing and is fastened to a solid steel cylinder, B, which also is the armature of an induction motor. Nearly all the weight of the rotating parts is supported by the attraction between the magnets A and B, which have a small clearance.

An electromagnet is used for heavy rotors and a permanent magnet for light ones. Slight excess weight is taken by a small thrust bearing which stabilizes the system. Magnetic flux through B does not change when B rotates, so there is no electromagnetic drag. Friction due to the magnetic support is minute.

Magnetic Suspension

The question arises as to whether or not the thrust bearing, the journal bearing, the cylinder B, and the

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shaft can be completely removed. This was accomplished at the University of Virginia in 1937 and has been greatly improved since then.

Fig. 2 shows a typical magnetic suspension. The rotor or its core, is made of some ferromagnetic material such as steel. It is attracted by the electromagnet which is composed of the solenoid and the iron core. The rotor is attracted upward with a force

$$F = M \frac{\partial H}{\partial z}$$

where M is the magnetic moment of the rotor and $\partial H/\partial z$ is the vertical gradient of the magnetic field, H. Consequently, the rotor will "fly up" to the electromagnet unless the current through the solenoid is properly regulated. This is accomplished automatically by the servo support circuit and the sensing coil.

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

No vertical or horizontal motion of the rotor can be observed with a microscope focused on the rotor surface. Measurements with an interferometer have shown that when the circuits are properly adjusted, vertical oscillation of the rotor has an amplitude of less than the wavelength of light.

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.

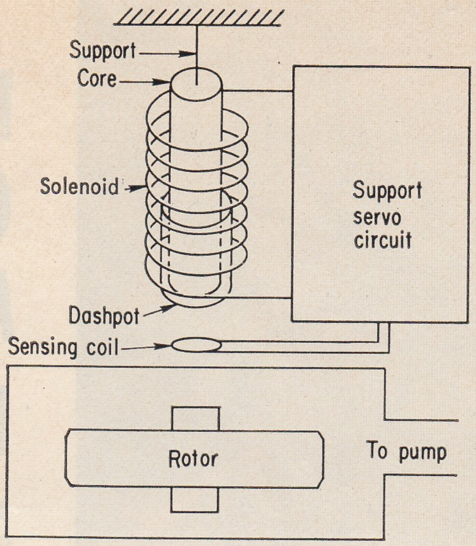

Fig. 2—Method of magnetically suspending rotor freely in vacuum.

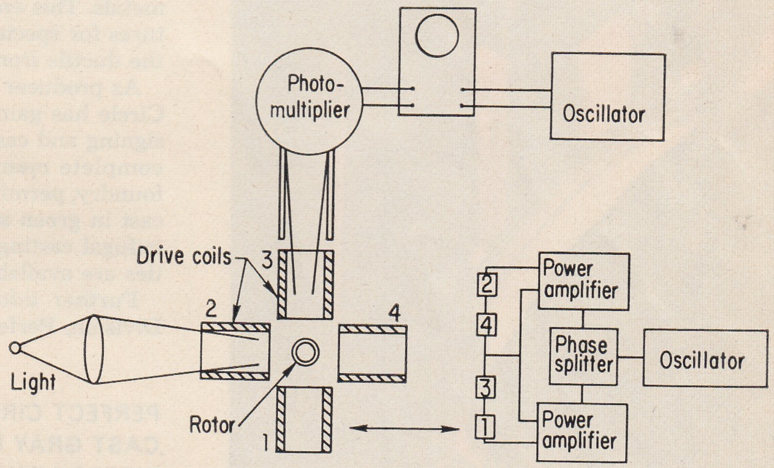

Fig. 3—Method of driving rotor and measuring its speed of rotation.

Rotor Speed

Fig. 3 shows a schematic diagram of a convenient method of spinning the rotor where small changes in temperature of the rotor are not important. The rotor serves as the armature of an induction motor the rotating magnetic field of which is produced by four field coils. The rotor also may be used as the armature of a synchronous or reluctance motor.

Where no heating of the rotor can be tolerated, as in the case of an ultracentrifuge, the rotor is driven to full speed by a long flexible shaft. Then the shaft is disconnected and the rotor is allowed to "coast" during sedimentation.

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 comparison. In some cases, it is convenient to count the signals from the photomultiplier cell directly with a high-speed counting system. Rotor speed is measured routinely to one part in 10^6.

With these drives, the only factor that limits the rotor speed is the strength of the rotor material. Rotors with weights of 100 to 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 have been obtained.

With properly constructed systems, the friction of the magnetic bearing is negligible compared to the air or gaseous friction on the rotor down to pressures of 10^{-7} to 10^{-8} torr.

Magnetically suspended rotors serve as excellent pressure gages over the range from 10^{-4} to 5×10^{-8} torr. A magnetically suspended ultracentrifuge rotor as shown in Fig. 2, when coasting freely at 600 rps inside a vacuum chamber where the air pressure is about 10^{-7} torr, loses only about 1 rps per day.

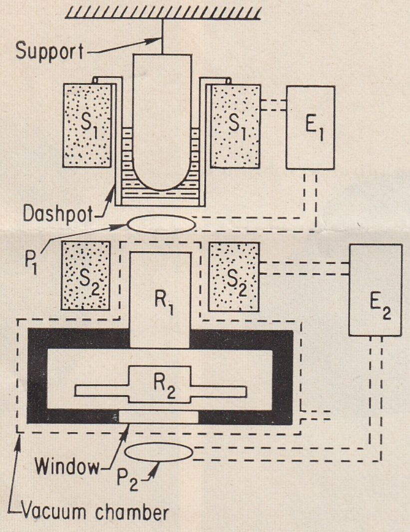

Fig. 4—Double magnetic suspension.

Rotor Damping

A "compound" arrangement is a convenient way of spinning a rod or tubular-type rotor, or of damping a rotor at both ends. A strong permanent magnet supports the rotor and a servo-controlled solenoid keeps the rotor stabilized. A dashpot of oil 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.

This arrangement can support rotors that spin about a horizontal axis. However, the end 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 magnetic bearings also have been devised.

Stabilization

By reducing residual gas pressure surrounding the rotor by freezing it out with liquid helium, by shielding stray magnetic fields, and by using damping mechanical vibrations, $(df/dt)/f$ is the order of 10^{-9} sec^{-1}, where df/dt is the change in the rotor speed f while the rotor is coasting. 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. 4 shows a double magnetic suspension that reduces the preceding two factors to extremely small values. Upper rotor R_1 is magnetically suspended by solenoid S_1 and vertically stabilized by servo circuit E_1. If a second ferromagnetic rotor, R_2, is 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.

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. 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.

If R_2 is made to spin at approximately the same speed as R_1 (within a few rps), the value of $(df/dt)/f$ 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.

In practice, 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.

R_1 is spun by a rotating magnetic field as in Fig. 3. 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.

Condensed by MACHINE DESIGN *from SAE Paper No. 810A, "Magnetic Bearings," presented at the Automotive Engineering Congress, Detroit, January, 1964, 5 pp.*

hydraulic

Cavitation and Flow Forces In Electrohydraulic Servomechanisms

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Analog simulation of the operation of an electrohydraulic servomechanism. Results are compared with a linearized analysis used to demonstrate the destabilizing effect of valve-flow forces. Various types of load and damping are considered.

It is shown that, as predicted by linearized theory, flow forces can seriously affect system performance. Their presence causes a reduction in open-loop static gain and, if the load is mainly of an inertial nature, these flow forces can induce instability. If the inertia load is small, viscous damping on the load is extremely effective in combating this

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