Magnetic-Suspension Ultracentrifuge Circuits

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High-speed rotor in vacuum is held in alignment by electronically controlled solenoid to give frictionless bearings that permit speeds up to 50,000,000 rpm, measured by comparing phototube output with WWV signals

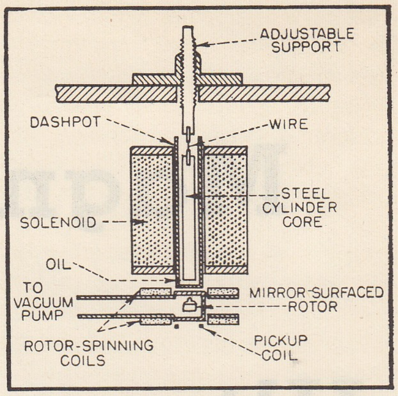

FIG. 1—Suspension for rotating mirror

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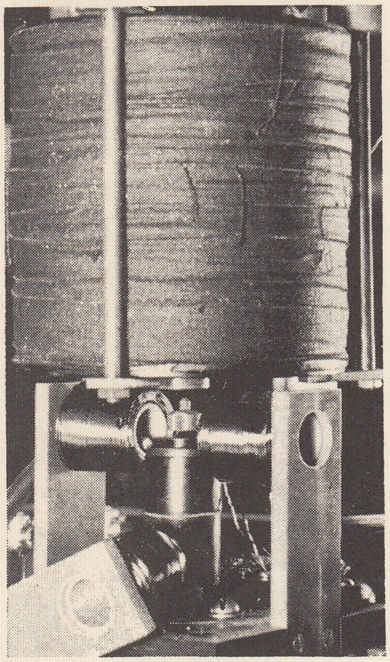
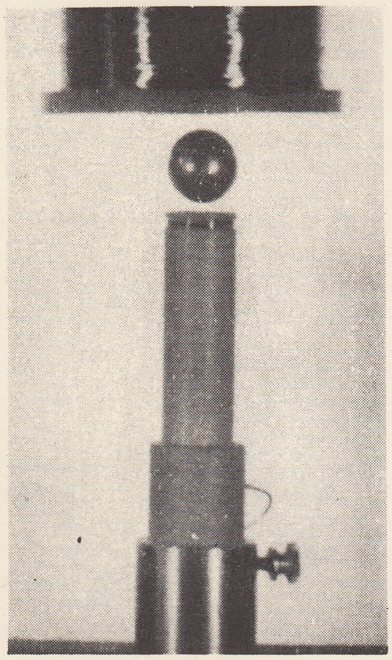
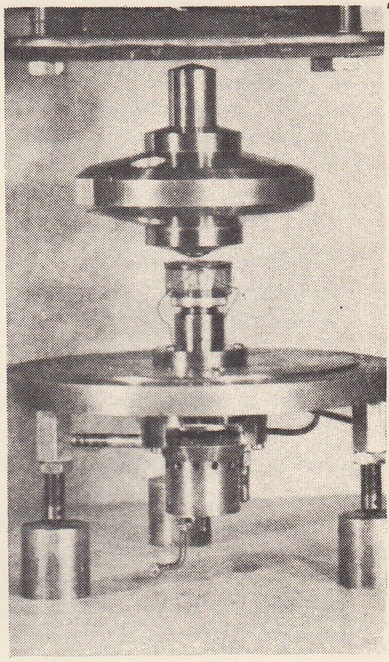

Suspension system for mirror-faced rotor. One of the four drive coils has been removed to show the rotor. Pickup coil is on pedestal directly under rotor


Magnetically suspended ¾-inch steel sphere, with drive coil and vacuum chamber removed. This setup is employed for checking bursting strength


Magnetically suspended ultracentrifuge 7.4 inches in diameter. Height-controlling pickup coil is directly under rotor, with air-turbine drive below

THE PROBLEM of finding suitable bearings for rotating bodies has been of major practical importance since man first started using rotating machinery. The efficiency of most rotating machinery is usually limited by the friction and useful life of the bearings. This is especially true where it is necessary to operate rotors near their bursting speeds.

This paper describes a magnetic support for high-speed rotors which has been under development at the University of Virginia for more than a decade and a half[1-7] and which has proven to be an almost ideal support bearing for a wide variety of high speed rotors.[8-11] Essentially, the same support technique is employed in spinning the rotors used in a number of different problems.

The method can be illustrated by referring to Fig. 1, which is a schematic diagram of a high constant-speed rotating mirror arrangement.[11]. The rotor, made of high-strength ferromagnetic material, contains mirror surfaces and spins at 20,000 rps. Any other type of ferromagnetic rotor could be used in the apparatus instead of the rotating mirror, but it was chosen for illustration here because it demonstrates a simple solution to a difficult rotating mirror problem. The rotor is freely suspended inside a glass vacuum chamber by the

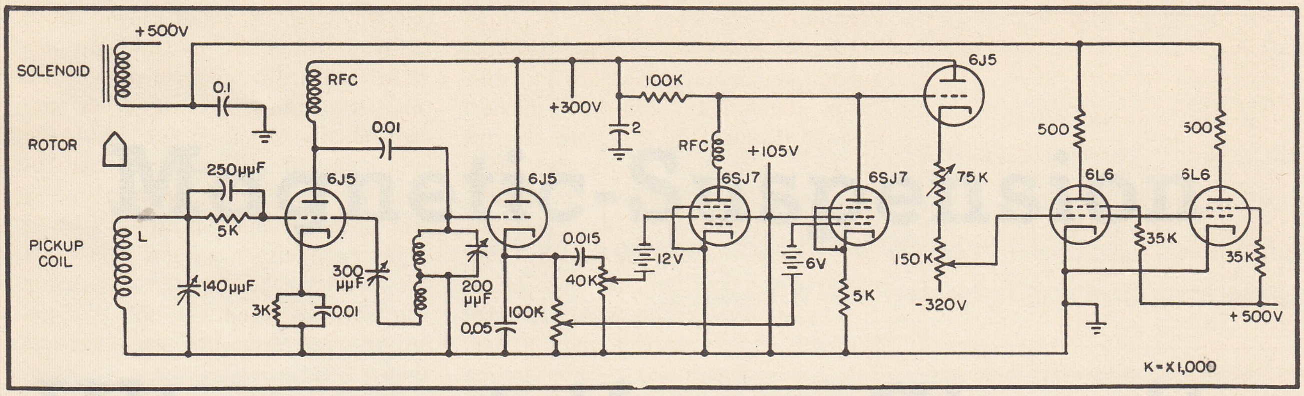


FIG. 2—Support circuit used to suspend small mirror-surfaced rotor in space, eliminating bearing friction

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axially-symmetrical diverging magnetic field of the solenoid situated above the chamber.

The vertical position of the rotor is maintained by the automatic regulation of the current through the solenoid with a servo circuit. The horizontal position of the rotor is determined by the symmetrical diverging magnetic field. The small pickup coil is the sensing element in the servo circuit, which is so arranged that as the rotor rises the current in the solenoid is decreased and vice versa. The circuit contains an antihunt arrangement which prevents vertical oscillations of the rotor.

Although the rotor automatically seeks the strongest part of the field, which is on the axis of the solenoid, it is necessary to provide horizontal damping to prevent oscillations about the axis of rotation when the rotor is disturbed. This is accomplished by hanging the steel cylindrical core of the solenoid by a small wire from an adjustable support, like a pendulum, in a dashpot of oil. The mass and size of the core depend upon the mass of the rotor and are so chosen that the lower end of the core follows the oscillations of the rotor and damps them out. When properly adjusted, no movement, either horizontal or vertical, can be observed in a 50-power microscope when focused on scratches on the rotor.

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The rotating mirror shown in Fig. 1 is made of hard, high-strength alloy steel. It is 0.5 inch from the bottom to the tip of the cone, and its six flat mirror faces, each 0.25 inch wide, are covered with a thin coating of aluminum. The cylindrical core of the solenoid is a cold-rolled steel rod 0.44 inch in diameter and 3.88 inches long. The support wire is 0.018-inch piano wire 0.085 inch long. The dashpot is a flat-bottomed glass tube containing SAE No. 10 motor oil. The solenoid is wound on a Bakelite frame with 25,000 turns of No. 28 insulated copper wire. It has an inductance of about 20 henrys and a resistance of approximately 1,000 ohms. The rotor is spun by two pairs of coils which produce a rotating magnetic field.

Support Circuit

Figure 2 shows one of several different circuits that may be used for supporting the rotor. The pickup coil *L* is in the grid circuit of a tuned-grid-tuned-plate 5-mc oscillator. If the oscillator is properly adjusted, a downward movement of the rotor will change the impedance of the pickup coil to lower the amplitude of the oscillation in the circuit. The d-c potential appearing across the cathode resistor is proportional to the amplitude of the oscillations and serves as a measure of rotor height. A portion of this potential is used as the direct error signal.

In parallel with the cathode resistor is an R-C differentiating network which gives a signal across the resistance proportional to the time rate of change of rotor height. This derivative signal effectively damps the up-and-down motion of the rotor.

Error Signal

The error and derivative signals are separately amplified, mixed and applied to the grid of a cathode follower. The combined signal is next applied to the grids of the 6L6 power tubes and regulates the current through the solenoid.

The magnitudes of the error or direct signal and of the derivative signal can be separately adjusted so that their proper relative and absolute values can be found. An exact theoretical analysis of the circuit is rather complicated, but an approximate solution assuming linearity of the elements is not difficult[12]. Several different pickup devices may be used instead of the coil in Fig. 1 and 2. A photoelectric pickup is especially useful, and has been used for the magnetic suspension of very small rotors[9] and

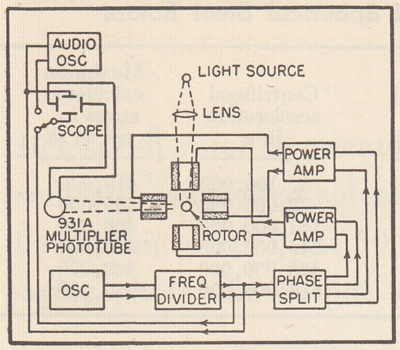

FIG. 3—Method of driving rotor and measuring its speed

in the magnetic-suspension microbalance.[9, 18]

The rotor is spun by a rotating magnetic field produced by two pairs of coils outside the vacuum system. Standard power circuits[11] produce the alternating current through these coils.

The drive system and the method of measuring the rotor speed are shown in Fig. 3. The oscillator frequency is generated by a 0.1-mc piezoelectric crystal-controlled electron-coupled oscillator. The crystal is thermostatically controlled and the output is calibrated by beating the 100th harmonic with the 10-mc WWV signal. The frequency is determined to about one part in 10^7, although the oscillator frequency is probably constant to one part in 10^8. The frequency is then divided by a factor of 5, the result passed through a phase splitter, and the two outputs separately amplified and transformer-coupled to the power circuit which in turn supplies the power to the drive coils for the rotating mirror.

Light is either reflected or scattered from the rotor into a multiplier phototube in such a way that each revolution produces one flash of light on the tube. The output of the tube is amplified and applied to one pair of plates of an oscilloscope. A comparison frequency, supplied by an audio-frequency oscillator during the period of rotor acceleration and by the drive-frequency source or WWV at operating speed, is applied to the other pair of oscilloscope plates. From the resultant Lissajous figure, the rotor speed is determined.

In order to bring the rotor to operating speed, the glass vacuum chamber surrounding the rotor is evacuated to less than 10^{-6} mm mercury pressure. The support circuit is then turned on and the rotor suspended. The drive circuit is next started and the rotor begins to spin. The rotor operates as a high-resistance armature of an induction motor during the acceleration period. When the speed of the rotor reaches about 50 rps below the frequency of the power source, the rate of acceleration falls off but the rotor continues to increase in speed. If the gas pressure surrounding the rotor is below 10^{-6} mm of mercury the friction is so small that the rotor speed will approach the frequency of the rotating magnetic field, then lock in and spin with the same frequency as that of the oscillator. However, this process usually takes more than an hour.

In practice, when the rotor acceleration begins to decrease, the crystal oscillator is disconnected from the phase-inverter and an audio oscillator substituted whose frequency is about 50 cycles above the frequency of the crystal-controlled drive circuit. The rotor is allowed to accelerate until it reaches a value just above the desired operating speed. The audio oscillator is then disconnected and the crystal control substituted. The rotor soon locks in and operates in the same way as the armature of a synchronous motor.

Because of the very low rotor friction and the small power input to the rotor, in a few minutes after locking in no observable hunting (less than 10^{-8} radians per sec) can be observed. Since the rotor speed is 10^5 radians per sec, the possible error due to hunting is less than one part in 10^8. With an input to the drive coils of 150 watts, the rotating mirror accelerates at the rate of about 1,000 rps per minute as long as the slip is greater than 50 cps.

Rotor Temperature

When the rotor is held stationary and the drive circuit operated until temperature equilibrium occurs, the rotor temperature increases less than 10 degrees C. This should give maximum heating. When it is desired to avoid heating in the rotor during the acceleration period, the rotor may be accelerated by magnetizing it transversely and letting it operate like an armature of a synchronous motor in which the drive frequency is increased at the same rate as the rotor speed increases. In this way practically no eddy currents are generated and the temperature of the rotor remains constant. The temperature of the rotor may be determined while it is spinning by measuring its thermal radiation.

Since the axial magnetic field is symmetrical over the rotor, no eddy currents are induced and there is no electromagnetic drag

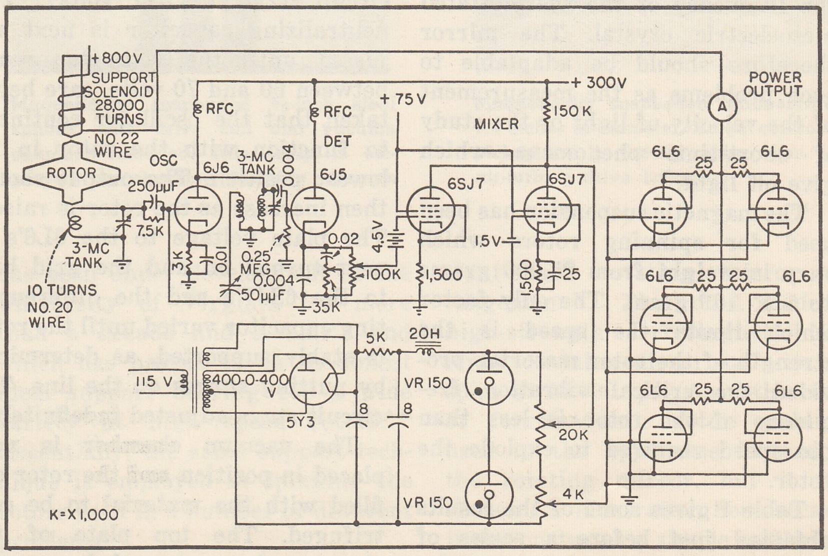

FIG. 4—Support circuit for large rotor (over 2 lb) in which liquid-filled cell can be inserted for analytical research involving sedimentation measurements. Bursting strength of rotor is only factor limiting angular speed

due to the support. There probably is some slight friction, but it is too small to observe. If the rotor is spun to operating speed and then allowed to coast, practically all of the observed deceleration of the rotor can be accounted for as due to residual gaseous friction on the rotor even at gas pressures below 10^{-6} mm of mercury. For a spherical rotor of radius r, density d and absolute temperature T surrounded by a gas of molecular weight M and pressure p, it can be shown that approximately

$$\log_e \frac{N}{N_o} = -\frac{5p}{rd}\left(\frac{M}{2\pi RT}\right)^{1/2}(t - t_o) \quad (1)$$

where N_o is the number of rps at the time t_o and N is the number of rps at the time t.

It is interesting to calculate the Q for a magnetically suspended rotor, which equals 2π (total energy of rotor)/(energy lost per cycle). For an all-steel-spherical rotor spinning at 300 rps the observed deceleration was about 1 rps in 4 days when the air pressure surrounding the rotor was less than 10^{-5} mm of mercury, which gives a Q of between 10^8 and 10^9.

Uses of Magnetic Suspension

The speed of the rotating mirror described above was determined to about one part in 10^7, which was the estimated reliability of the received frequency from WWV. It spun at 20,000 rps with a constancy which was at least equal to that of the frequency of the thermostated piezoelectric crystal. The mirror therefore should be adaptable to such problems as the measurement of the velocity of light or the study of short-time phenomena which give off light.

The magnetic suspension has been used for spinning rotors which vary in weight from 25,000 grams to 5×10^{-5} gram. The only factor which limits the speed is the strength of the rotor material, provided the critical vibration frequency of the rotor is less than the speed required to explode the rotor.

Table I gives some of the results obtained just before a series of spherical rotors exploded. The spherical rotors were carefully selected steel ball bearings. All of these steel rotors that were free from flaws attained approximately the same peripheral speed before exploding. This is in agreement with theory. The maximum stresses, which were at the center of the rotor, were calculated on the basis of elastic theory and hence may be too large. The maximum centrifugal force of over a half-billion times gravity was obtained with the smallest diameter rotor.

Table I—Bursting Speeds of Spherical Steel Rotors

Rotor diam in mm	Rotor speed in rpm	Peripheral speed in cm per sec	Centrifugal acceleration in g	Maximum calculated stress in lb per sq in.
3.97	4,420,000	96,000	47,100,000	410,000
2.38	7,410,000	92,500	72,000,000	385,000
1.59	12,660,000	105,000	143,000,000	498,000
0.795	23,160,000	96,500	240,000,000	420,000
0.521	37,980,000	104,000	428,000,000	488,000
0.398	48,000,000	100,000	515,000,000	454,000

This type of ultracentrifuge uses magnetic support in conjunction with an air-driven turbine drive under the rotor. To operate the centrifuge, the brass vacuum chamber is removed and the support circuit of Fig. 4 is adjusted until the rotor is stably supported. This circuit adjustment is not difficult and may be carried out as follows. With the rotor resting and the plate supply to the 6L6's switched off, the grid, plate and neutralizing capacitors are adjusted for maximum output as determined by a high-resistance voltmeter in the detector circuit (200 to 250 volts). The neutralizing capacitor is next adjusted until the voltmeter reads between 60 and 70 volts, care being taken that the oscillator continues to function with the rotor in its lowest position. The output should then increase as the rotor is raised. The plate voltage to the 6L6's is next turned on and the grid bias to the 6SJ7's and the differentiating capacitor varied until the rotor is stably supported, as determined by putting surges on the line. The circuit stays adjusted indefinitely.

The vacuum chamber is next placed in position and the rotor cell filled with the material to be centrifuged. The top plate of the chamber is next sealed on with vacuum wax and the solenoid and core are mounted and adjusted. In the meantime, the electrical circuits have been allowed to warm up and the cooling fluid started circulating through the cooling coils attached to the chamber. The vacuum pumps are then started and the rotor is supported by the solenoid in its running position. When the pressure in the chamber is 10^{-5} mm of Hg or less, air is admitted to the turbine and the rotor is accelerated until operating speed is reached. The turbine is then disconnected and the rotor continues to coast smoothly during the period of the experiment.

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Another important use of the magnetic suspension is in the vacuum-type ultracentrifuge.[8] In one instrument, the rotor is 18.8 cm in diameter and carries a sector-shaped cell with quartz windows in which the sedimentation of the material is observed. From these observations, the molecular weights of the substances in solution in the cell may be determined.

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