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Magnetic Suspension for Small Rotors*

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A magnetic suspension for small rotors has been developed which employs scattered light to regulate the vertical height of the rotor. Upon entering a horizontal beam of light the rotor scatters or reflects light into a photo-electron multiplier cell. This cell actuates an electronic circuit which in turn regulates the current through the supporting solenoid in such a way as to maintain the ferromagnetic rotor at the desired vertical position. Rotors with diameters down to 0.004″ have been stably supported. A $\frac{1}{64}''$ rotor was spun to an estimated speed of 800,000 r.p.s. which gave a centrifugal field in excess of one-half billion times gravity. Besides providing a support for rotors, the apparatus may be used as an analytical balance for weighing materials inside a vacuum chamber. It detects changes in mass of from 10^{-8} to 10^{-9} gram. Other uses also are indicated.

IN order to produce high centrifugal fields it is necessary to use as small rotors as possible. This results from the fact that for a homogeneous elastic rotor of a given shape the bursting speed depends upon the square of the peripheral speed and is independent of the radius. In other words, for a given shape of rotor made of an elastic material $v^2=w^2r^2=K$ where w is the angular velocity, r is the radius of the rotor, v is the maximum peripheral speed and K is a constant. Consequently, the maximum centrifugal field $w^2r=K/r$ and thus increases as r becomes smaller.

In previous reports methods of spinning rotors of various diameters to their bursting speeds have been described.[1] The rotors were suspended in a vacuum by an axial magnetic field and spun by a rotating magnetic field. In this method the vertical stability of the rotor is maintained by the effect of the rotor on the impedance of a small "pick-up" coil placed below or above the rotor and connected in the grid circuit of a high frequency oscillator which in turn regulates the current through the supporting solenoid. As the rotor moves upward or downward, the current through the supporting solenoid is automatically decreased or increased respectively by the proper amount to maintain the rotor at the desired vertical position. Such a magnetic suspension is extremely stable and in practice has a resistance to rotation much smaller than the air friction on the rotor even when the air surrounding the rotor is at a pressure the order of 10^{-6} mm of Hg. However, when the size of the rotor becomes very small (below 0.02″ in diameter) the effect of the rotor on the impedance of the pick-up coil is reduced and consequently the adjustments of the circuits required to maintain vertical stability of the rotor become increasingly difficult. In this paper a magnetic suspension is described in which the vertical height of the rotor is determined by the amount of light scattered by the rotor into a photoelectric "pick-up". With this arrangement much smaller rotors can be suspended and spun than with the previous method.

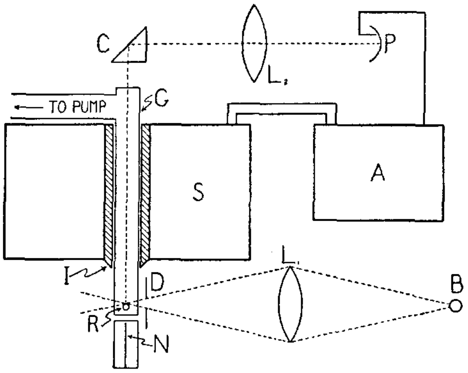

Fig. 1.

Figure 1 shows a schematic diagram (not to scale) of the method. The rotor R is surrounded by an evacuated glass tube G which is mounted coaxially with the supporting solenoid S. Light from a lamp B with a straight incandescent filament perpendicular to the page is brought to focus by a moderately long focus lens L_1 along a diameter of the glass tube in such a way that a thin horizontal beam or sheet of light crosses the glass tube. As the rotor R is pulled upward by the magnetic field of the solenoid S, it enters the light beam and scatters or diffusely reflects light upward through the glass tube, right angle prism C and lens L_2, which concentrates the light on the photo-electron multiplier cell P.

The current signal in P is amplified by the electronic circuit A and made to regulate the current through the solenoid S. When properly adjusted the current in S is automatically regulated so that the vertical position of the rotor remains constant. The horizontal stability is of course provided by the axial magnetic field of the supporting solenoid. A small iron wire N surrounded by a damping fluid and placed below and outside the vacuum chamber G served to damp out any horizontal motion of the rotor.

The solenoid S consisted of 23,000 turns of No. 28 copper wire wound on an insulated Bakelite frame. Its resistance is approximately 1300 ohms and its inductance with the iron core B is about 30 henrys. The iron

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[1] Beams, Young, and Moore, J. App. Phys. **17**, 886 (1946). See J. W. Beams, Wash. Acad. Sci. **37**, 221 (1947) for other references.

core is a cold rolled steel tube 4 inches long, 0.5 inch internal diameter, and 0.1 inch wall thickness. In the first experiments, it had a very narrow vertical slit to prevent eddy currents but this was later found unnecessary. In most of the experiments the current through the solenoid varied from 30 to 70 milliamperes depending upon the size and desired position of the rotor. It was found that the number of turns in the solenoid is not critical, as several different solenoids with varying numbers of turns, resistances and inductances were used successfully. In most of the experiments 500 to 1500 ohms resistance was placed in series with the solenoid described above.

In the majority of the experiments a 1P28 photo-electron multiplier tube was used at P to pick up the light signal although both 931A and 1P21 tubes were used successfully. With most of the circuits used it was an advantage to select photo-multiplier tubes with as low a dark current as possible. Also for the smallest rotors it was found desirable, although not necessary to keep the tube at dry ice temperature in order to maintain the "noise" or current fluctuations at a minimum.

Figure 2 is a diagram of an electronic circuit (A. Fig. 1) which has operated very satisfactorily for long periods of time without adjustment. Also it has been used for supporting rotors over a wide range of sizes and weights. It is composed of ordinary standard parts and is easy to adjust. The signal from the photo-electron multiplier cell P is first amplified by T_1 (6J5) and then applied to the grid of the cathode follower T_2 (6J5) which, in addition to reproducing the signal, generates a derivative of the signal. The signal which occurs across R_7 is applied to the grid of T_4 (6SJ7) while its derivative produced by the circuit R_8C_2 is applied to T_3 (6SJ7) in parallel with T_4. The two signals are mixed and applied to the grid of T_5 (6J5) which is a second cathode follower and then on to the grid of the power tube T_6 (6L6) which regulates the current through the solenoid. The resistance capacity combination $R_{11}C_5$ is not necessary although it makes possible somewhat easier adjustments. The resistances R_8, R_{11} and R_2 and the capacities C_2 and C_5 should be variable in order to facilitate adjustment. The filaments of T_2 and T_5 were each heated by separate insulated storage batteries.

It will be observed that as the rotor rises into the light beam the scattered light falling on P is increased and the current through the supporting solenoid consequently decreased. As a result the rotor falls and scatters less light into P which in turn increases the current through the supporting solenoid S and raises the rotor. Clearly this would give rise to oscillations were it not for the derivative signal generated by the C_2R_8 combination. The phase of this derivative signal is adjusted to be from 70° to 90° out of phase with that of the original signal and hence damps the oscillations. When this adjustment is made properly no vertical motion of the rotor is observable even through a microscope focused on scratches on the rotor. The values given in Fig. 2 were for supporting a 15-mil steel spherical rotor about 1.45 cm below the end of the tubular iron core, but they are not critical with rotor size.

The support circuit (Fig. 2) was found to operate just as satisfactorily with the first stage of amplification T_1 removed. This, of course changes the phase relations so that as the rotor moves out of the light beam the current through the supporting solenoid is decreased and *vice versa* so that the rotor is positioned on the top edge of the light beam rather than on the bottom edge as in the case of the first arrangement. With the first amplification stage out of the circuit it is necessary to increase the signal by increasing the resistance R_3 or the potential on P or both. In practice it is usually found more convenient to use the whole circuit as shown in Fig. 2.

The rotor was spun by a rotating magnetic field produced by an alternating current in two pairs of coils (not shown in Fig. 1) surrounding the rotor but outside the glass vacuum chamber. The frequency of the rotating magnetic field or the a.c. current in the coils is set equal to the desired running speed of the rotor and is controlled piezoelectrically. The rotor is accelerated in a way similar to that of an armature of an induction motor. It should be noted that although the "slip" is large, the comparatively high electrical resistance of the steel rotor gives a satisfactory starting and accelerating torque. It has been shown previously[1] that the frictional drag on a spinning rotor supported magnetically in a high vacuum is so small that the rotor accelerates to speed as an induction motor and then "locks in" and spins in synchronism with the rotating magnetic field without hunting. Except for the piezoelectric control, the driving circuit is similar to that used previously. The power supplied to the coils is about 10 watts and it is necessary to cool them with air circulated by an electrically driven blower. The acceleration of the rotor varied with the size of the rotor but it usually took several hours to bring the rotors up to full speed. The temperature of the rotors was a few degrees above room temperature.

The rotor speed was measured by a photoelectric pick-up for rotor diameters of 20 mils and above. For rotors below 20 mils in diameter no satisfactory direct method has been found for measuring the highest rotor speeds so they must be estimated by indirect methods. However, in all of the experiments if the rotors are accelerated for a long enough period they will "lock in" and spin in synchronism with the rotating magnetic field so that the maximum speeds of the smaller rotors are determined by the respective frequencies of the driving circuits which of course are determined quite accurately by a frequency meter calibrated against W.W.V. With a 1/64-inch diameter steel spherical rotor kindly furnished by Mr. W. S. Pierce, Jr., Miniature Precision Bearing Company, estimated rotor speeds of 800,000 r.p.s. were obtained without exploding the rotor. This gives a centrifugal field on the periphery of over a half-billion time gravity.

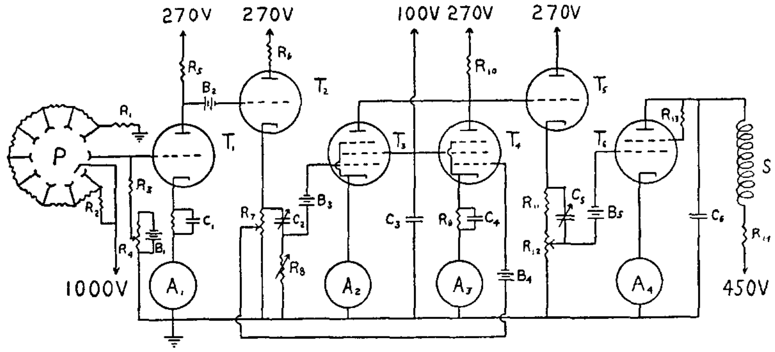

FIG. 2.

$R_1 = R_2 = R_4 = R_7 = 10^5$ ohms
$R_3 = 10^6$ ohms
$R_5 = 2\times10^5$ ohms
$R_6 = 10^3$ ohms
$R_8 = 5\times10^4$ ohms max.
$R_{10} = 2.7\times10^5$ ohms
$R_{11} = 5\times10^4$ ohms max.
$R_{12} = 3\times10^4$ ohms max.
$R_{13} = 2\times10^4$ ohms
$R_{14} = 1500$ ohms max.
$T_1 - T_2 - T_5 - 6J5$
$T_3 - T_4 - 6SJ7$
$T_6 - 6L6$

$B_1 = 2.1$ v
$B_2 = 135-225$ v (variable)
$B_3 = 4.6$ v
$B_4 = 10$ v
$B_5 = 45-135$ v (variable)
$C_1 = C_4 = C_6 = 0.1$ mf
$C_2 = 0.03-0.1$ mf
$C_3 = 0.3$ mf
$C_5 = 0.03-0.15$ mf
$S = 30$ h and 1300 ohms

As the diameter of the rotor is reduced below about 20 mils, it becomes more difficult to adjust the damping needle N (Fig. 1). The diameter of the steel or alloy needle N is made smaller than the rotor and usually is surrounded by water. So far, the requisite damping has been obtained by a tedious process of trial and error. It should be noted that any sudden vertical motion of a rapidly spinning rotor may set it into horizontal oscillation especially if the axis of the magnetic field is not exactly vertical so the power supplies to the electronic circuits must be well stabilized and the spinning rotor should be kept free of vertical motion.

The distance of the rotor below the core of the solenoid varies with the size of the rotor and shape of the core. For rotors below $\frac{1}{8}$ inch in diameter, a satisfactory working distance with the solenoid described above is about 1.5 cm. It will be observed that for rotors with dimensions small in comparison to their distances below the solenoid core, the force F on the rotor is approximately $M(dH/dX)$ where H is the magnetic field, X the distance along the axis of the field, and M the magnetic moment induced in the rotor by the field H. For soft iron (but not necessarily for hard steel) M is roughly proportional to μH so the lifting force $F \propto \mu H(dH/dX)$ where μ is the permeability of the rotor material. Consequently the proper rotor distance below the solenoid is determined by the shape and intensity of the magnetic field and may be varied over considerable ranges.

RESULTS

As mentioned previously the apparatus described in this paper was developed primarily for obtaining high centrifugal fields for use in a number of different studies. So far a series of experiments have been carried out on the bursting speeds of steel spherical rotors of different diameters. These results show that for the particular steel used, the maximum peripheral velocity obtained was approximately the same (10^5 cm/sec.) for all sizes of rotors tried. However, the probability that a given rotor would reach maximum peripheral speed increased markedly as the diameter of the rotor decreased. The explanation of this seems to be that as the rotor diameter is decreased the amount of material around the center of the rotor which is under maximum stress is decreased and consequently the probability of finding a flaw or crack in the stressed part of the smaller rotor is decreased.

Observations also have been made on the centrifugal fields necessary to pull films off of the periphery of the rotor. Since the thickness and density of the films are known the forces on the films can be calculated. In the highest centrifugal fields some of the "trash" laid down on the surface during the polishing process apparently was thrown off although further observations must be made before this can definitely be established. Attempts to use the apparatus for the study of possible molecular orientations by centrifugal fields also are in progress.

In one of the experiments a very narrow slit was placed at D in Fig. 1 in order to cut down as much light background as possible. However, in addition to cutting down the background it gave rise to a diffraction pattern the result of which was to give in effect a slow increase of light intensity as the beam was approached from the bottom or top. A 1/64-inch rotor was carefully supported in the lower region of the light beam. The pumps were then started and the system quickly evacuated to less than 10^{-5} mm of Hg. During this evacuation, the rotor was observed through a 30-power microscope and found that its height was considerably decreased. This was repeated several times and traced to the buoyancy of the air. The volume of the rotor was 3.36×10^{-5} cm^3 and its weight 2.6×10^{-4} gram. Further experiments were then carried out to determine the sensitivity of this balance and it was found that between 10^{-8} and 10^{-9} gram change in weight could be observed. Clearly this observation indicates that with the proper design the apparatus may be used as a most sensitive balance. Magnetic suspension balances have been used previously[2] but the present method affords much greater sensitivity and stability and the weighing can be carried out in vacuum, i.e., during a chemical reaction on surfaces, for osmotic pressure measurements, etc. A more detailed description of this application will be described later.

The lower limit to the diameter of rotor that can be supported by the above apparatus has not as yet been reached. The smallest rotor so far used was about 4 mils in diameter.

The writer wishes to express his appreciation and indebtedness to Mr. J. Dillon and Mr. W. Lucke for help with the electronic circuit.

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[2] John W. Clark, Rev. Sci. Inst. **18**, 915 (1948).