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THE MAGNETICALLY-SUSPENDED FREE GYROSCOPE

by

E. F. Kinsey J. W. Beams M. J. Saunders

NAVAL ORDNANCE RESEARCH LABORATORY
UNIVERSITY OF VIRGINIA
Charlottesville, Virginia

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INTRODUCTION

A critical limitation to the reliability and precision of gyroscope bearings is inherent "chatter," or "noise level." Such chatter occurs in all bearing types, including journal, ball, roller and air. In practice this is of an order of magnitude above the limit set by the natural Brownian motion. Also, even though one assumes that the rotating parts are in perfect balance (which is never entirely true), the bearings give rise to reactions on the rotor which cause it to precess.

Most gyroscope rotors spin in air, or other gases. The aerodynamic forces on the rotor thus produced appreciably disturb its motion. In addition, the rotor drive produces disturbances which are generally proportional to its power input.

When the above factors are considered it becomes clear that substantial improvements might be made if the gyroscope rotor were mounted in a high vacuum in substantially friction-free bearings and allowed to "coast" during those periods when it is in use. The bearings must be arranged so that the rotor turns freely about any axis in space. The "pick off" should not influence the gyroscope rotor and should be as free of noise as is practicable.

A preliminary attempt to justify the above observations has been made at the Naval Ordnance Research Laboratory and is reported below. The laboratory apparatus employed was designed to include test principles which, if established, might be incorporated in a practical instrument. Many of the results described in this paper have been previously reported during the past two years in quarterly reports from the University of Virginia to the Applied Physics Laboratory of The Johns Hopkins University.

I. PROBLEM CONSIDERATIONS

A series of experiments has shown (Refs. 1, 2 and 3)[1] that the friction on a symmetrical steel rotor spinning about a vertical axis while magnetically suspended in a vacuum chamber can be completely attributed to air friction. This is true even at pressures as low as 10^{-6} mm of mercury. The friction due to the magnetic suspension is negligible because the magnetic field across the rotor is symmetrical with respect to the axis of rotation and no eddy currents are produced. Measured decelerations of a steel sphere surrounded by air at a pressure of 10^{-6} mm of mercury, coasting at an angular velocity just below its bursting speed, show that it would rotate for approximately two years.

However, if the axis of rotation makes a large angle with the axis of the magnetic field, eddy current and magnetic hysteresis introduce appreciable rotor damping or friction. Also, with a conducting ferromagnetic rotor these effects constrain the axis of rotation to coincide with the axis of the magnetic field. Clearly this is a distinct advantage for a centrifuge rotor or rotating mirror but must be eliminated if the rotor is to serve as a free gyroscope.

Three torques are produced when a conducting ferromagnetic sphere rotates about an axis which makes a large angle with the axis of the supporting magnetic field: (a) a torque due to eddy-current losses, (b) a torque due to hysteresis or magnetic memory, and (c) a torque which is produced by lack of homogeneity of the magnetic material and/or the fact that the rotor is not spherical. If the magnetic support is to suspend a free gyroscope rotor these torques must be eliminated.

The obvious solution to the problem of the first torque is to make the ferromagnetic rotor non-conducting, while the elimination of

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[1] References are listed on page 11 of this report.

the second may be accomplished by making the rotor of material which has negligible magnetic memory. The elimination of the third torque is a mechanical problem, one of achieving complete homogeneity of the material and milling the sphere to exact tolerances.

II. CONSTRUCTION OF THE GYROSCOPE

After experimenting with a number of rotor materials including ferrites, permalloys, Mumetal and other ferromagnetic alloys which were unsatisfactory, a rotor made of powdered molybdenum permalloy (whose particle size was about three mils in diameter) suspended in a non-conducting, non-magnetic phenolic binder and pressed together by a pressure of about 200 tons/in.^{2}, proved to be the best material found so far. The non-conducting binder prevents eddy currents but lowers the effective permeability to about 120 gausses/oersted. In the magnetic field of the solenoid (about 200 oersted), the material is saturated so that the so-called "rotational hysteresis" is extremely small (Ref. 4).

As a result, this material eliminated the eddy-current effect and reduced the magnetic memory and hysteresis to negligible values with rotor speeds up to 200 rps, the maximum speed attainable before the three-quarter inch spherical rotor explodes.

A schematic diagram of the apparatus is shown in Fig. 1 (not scaled). The spherical ferromagnetic rotor, B, is freely suspended inside the non-magnetic vacuum chamber, C, by the axial magnetic field of the solenoid situated above the chamber. Such a rotor seeks the strongest parts of the magnetic field so that if given a horizontal displacement it is pulled back toward the axis of the solenoid and hence is stable horizontally. Figure 2 is a photograph of the device with the vacuum chamber removed.

In order to maintain the rotor in a given vertical position, a small "pickup" coil, P, is placed either above or (better) below the rotor as shown in Figs. 1 and 2. This pickup coil is in the grid

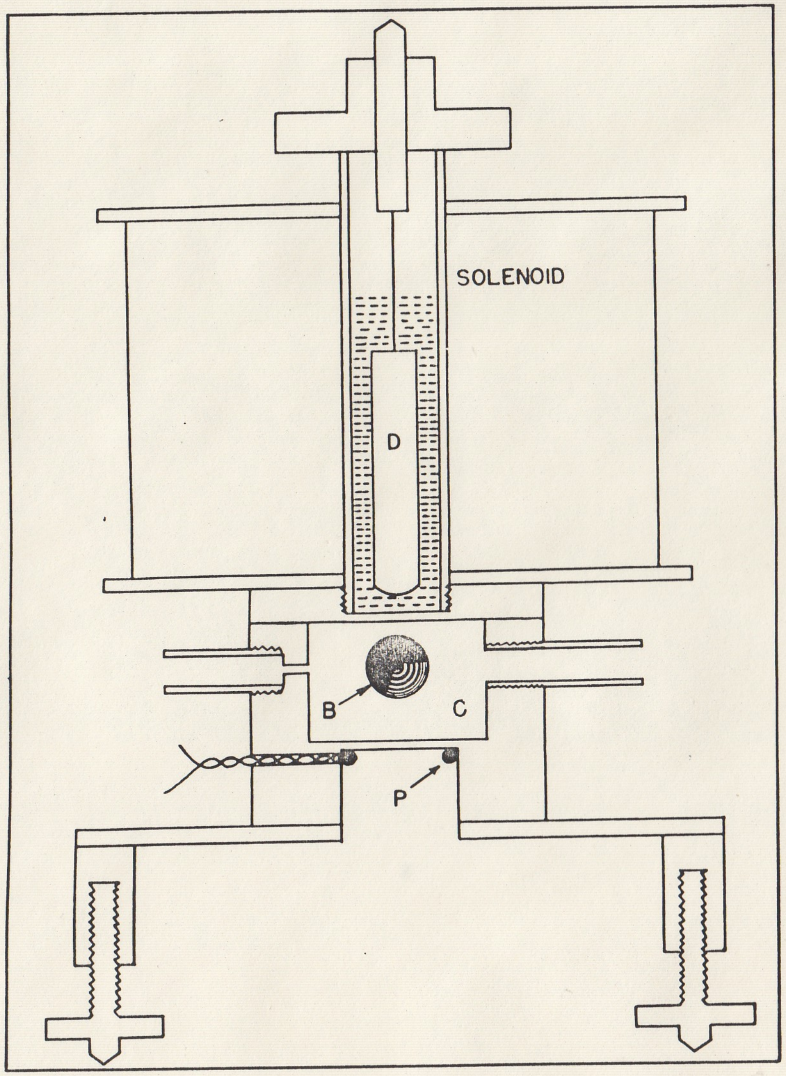

Fig. 1 DETAILS OF THE FREE GYROSCOPE

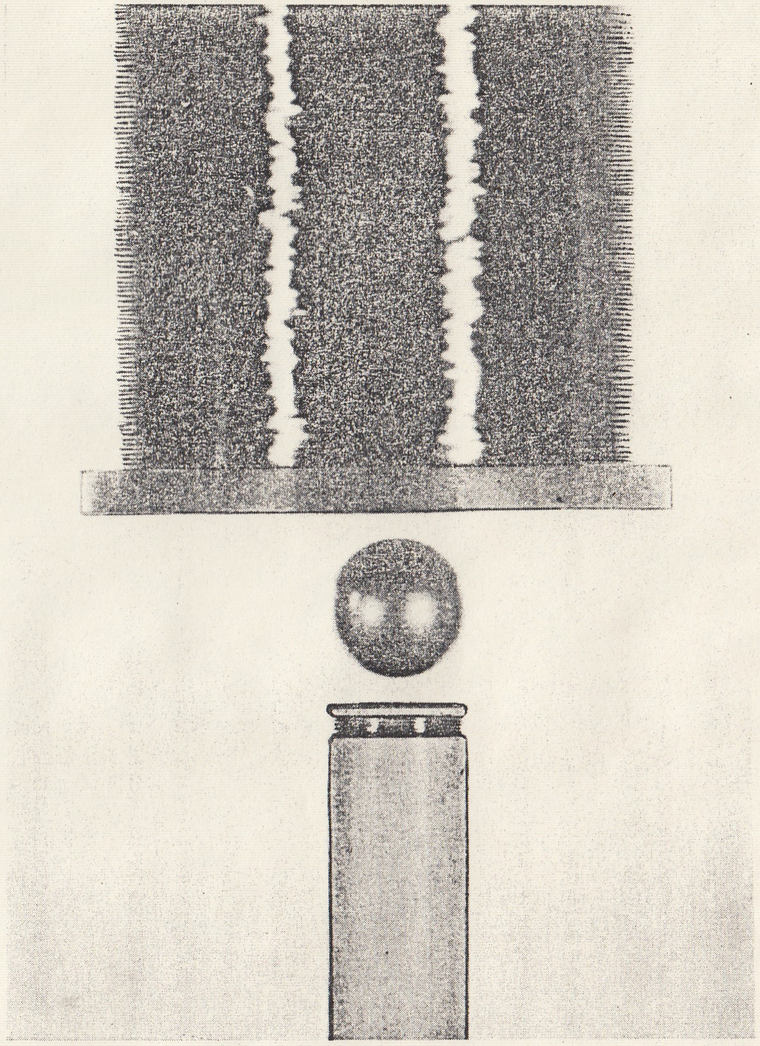

Fig. 2 THE GYROSCOPE WITH CHAMBER REMOVED

circuit of a tuned-grid, tuned-plate oscillator which in turn regulates the current through the solenoid. A schematic diagram of the electrical circuit used to keep the rotor, B, in the desired vertical position is shown in Fig. 3.

In order to further increase the horizontal stability of the rotor, the core, D, of the solenoid is hung as a pendulum by a small wire in a dashpot filled with No. 10 motor oil. If the rotor is moved sidewise, the core, D, follows and the motion is automatically damped. In many of the experiments reported in this paper, the core was four inches long and one-half inch in diameter. A test tube of three-quarter-inch diameter was flattened on the bottom to serve as the oil dashpot. The solenoid consisted of 25,000 turns of No. 25 copper wire. Its resistance was 600 ohms and its inductance was 20 henrys. The pickup coil, P, comprised seven turns of No. 30 copper wire bunch-wound in a diameter of one inch.

Vertical movement of the rotor changes the impedance of the pickup coil which is in the grid circuit of the oscillator operating at a frequency of ten megacycles per second. The change of impedance of the coil produces a corresponding change of potential across the cathode-follower circuit of the type-56 detector tube. This error signal is impressed on the grid of one of the type-6SJ7 tubes, while the derivative of the signal is impressed on the grid of the other type-6SJ7 tube, the two serving as a mixer-amplifier circuit. The mixed signal appears on the grid of the type-6J5 tube, a cathode follower whose output is applied to the control grids of the three type-6L6 tubes in parallel. These regulate the current through the supporting solenoid. The derivative signal is used to damp out effectively all vertical oscillations of the supported rotor. Under operating conditions, no vertical movement was detected by observing scratches on the stationary rotor through a 50-power microscope.

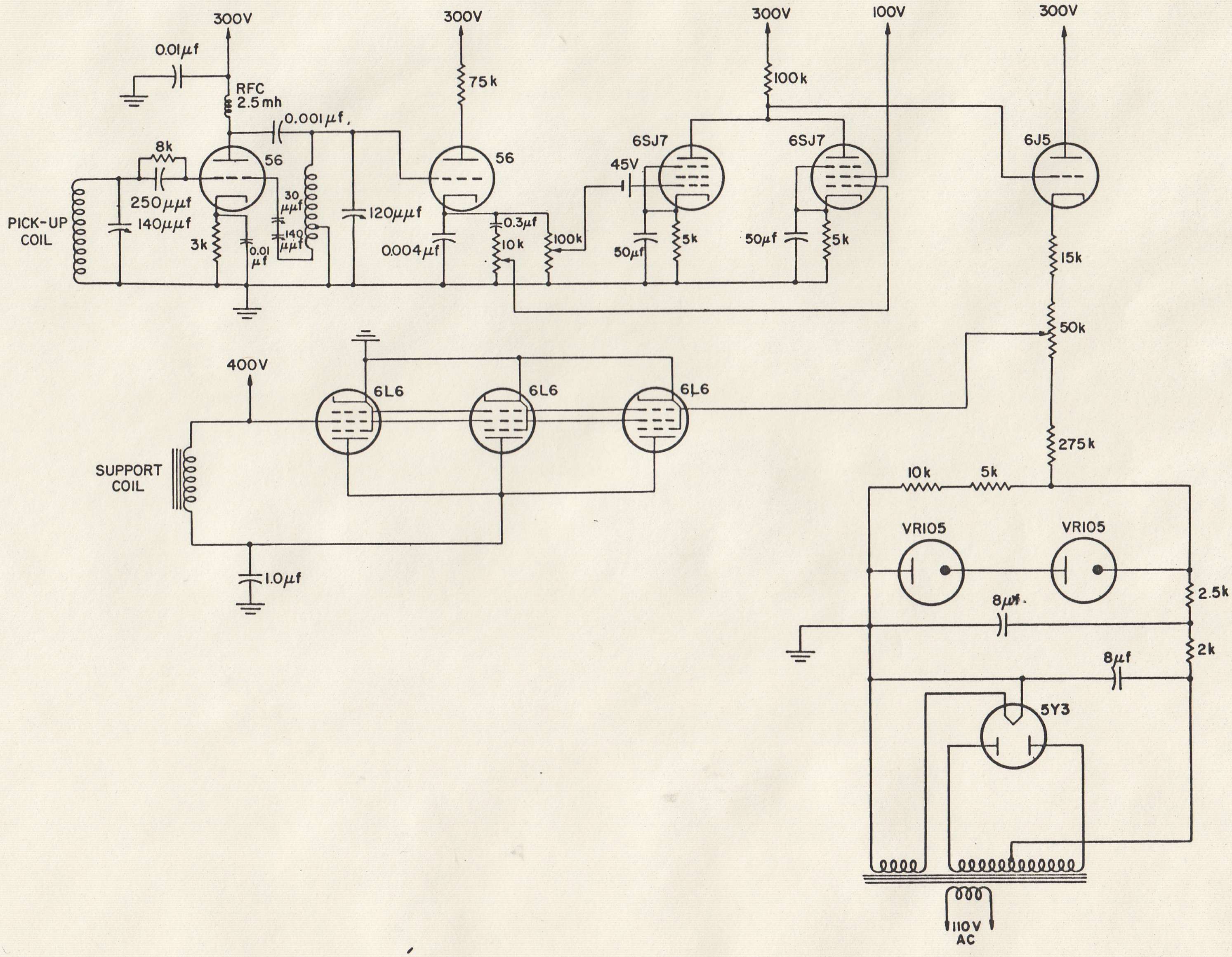

Fig. 3 THE MAGNETIC-SUSPENSION CONTROL CIRCUIT

III. METHOD OF GRINDING THE ROTORS

The development of a method of grinding the pressed powdered composition material into an accurate sphere was a time-consuming task. However, a simple procedure was finally developed. The material, cut from a toroid furnished by the Arnold Engineering Company, was sawed into cubes and filed by hand into approximate spheres of three-quarter-inch diameter. Four of these rough spheres were placed in a grinding machine, such as that shown in Fig. 4, where they lay in the groove, C (the diameter of the rough spheres was approximately 0.04 inch larger than the groove). The top piece, A, was chucked in a drill press and lowered while rotating until the groove contacted the spheres with a pressure of approximately eight ounces. A paste of magnesium-oxide powder was used as a grinding material. The grooves were periodically cleaned of chips. By this procedure, the spheres were ground to an accuracy of 0.003 inch in less than an hour.

One of the spheres so produced was placed in a glass funnel, as shown in Fig. 5, the inside of which was covered with paper, or cloth, coated with jeweler's rouge. Air was admitted through the stem of the funnel at the pressure required to cause the sphere to spin. Generally, at least for short intervals of time, the sphere spins freely on an air cushion and consequently about its axis of maximum moment of inertia. As a result the high spots on the rotor travel faster than the valleys so that, when the rotor touches and rubs on the paper, the high spots are ground off and it thus becomes a more accurate sphere. By this process the rotor became spherical to an accuracy of 0.0005 inch in about an hour.

By virtue of this accuracy, undesirable motion due to geometry is considerably less than that due to inhomogeneity of the material. At the present time the inhomogeneity is too great for satisfactory

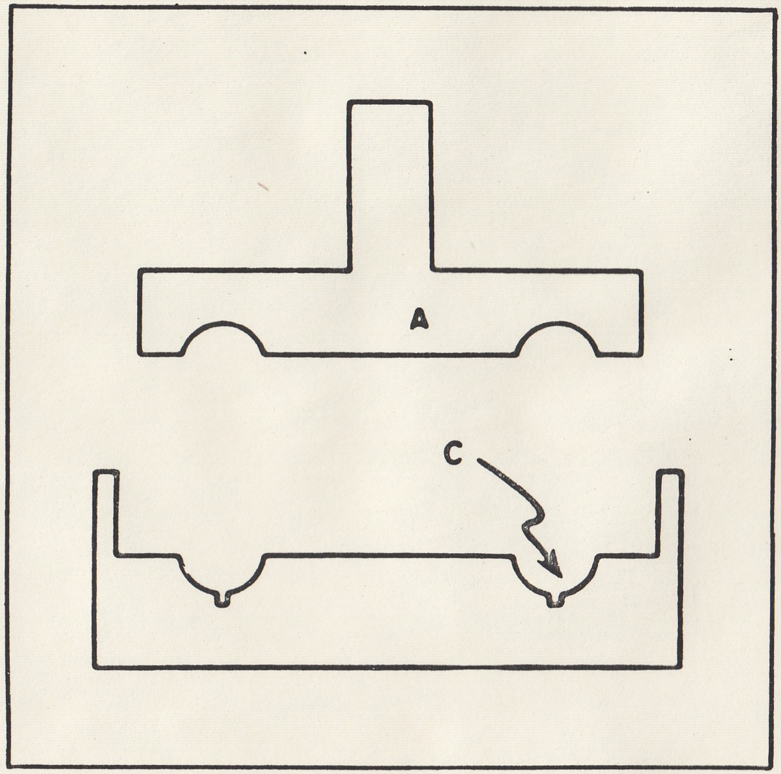

Fig. 4 SECTIONAL VIEW OF THE ROTOR GRINDING MACHINE

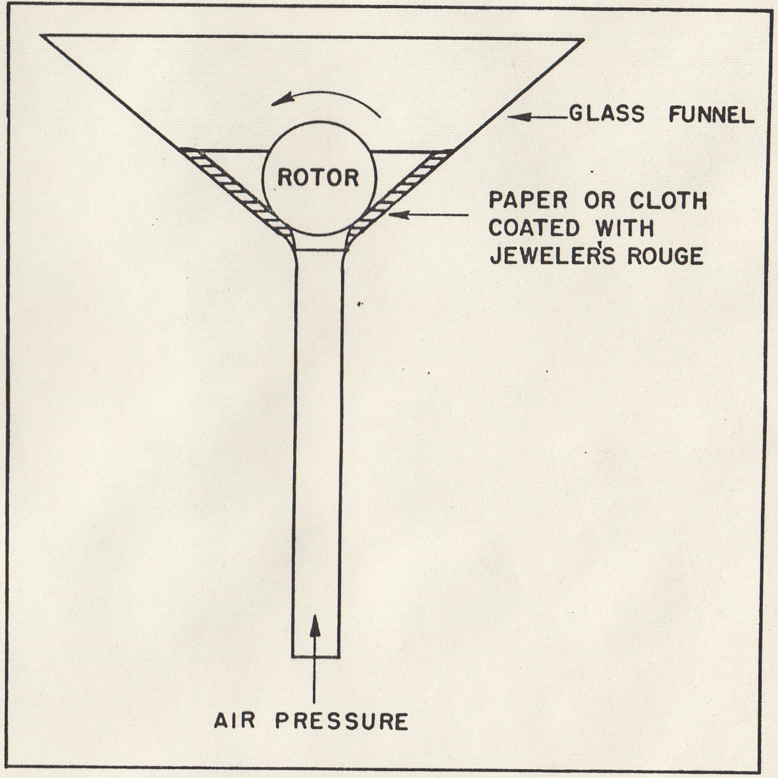

Fig. 5 APPARATUS USED TO PRODUCE THE FINISHED ROTOR

long-time operation of the rotor and is the principal limiting factor to the use of such a sphere as a gyroscope.

IV. ROTOR DRIVE METHODS

In experiments with steel spheres the rotor was driven by a rotating magnetic field in a manner similar to the acceleration of the armature of an induction motor. However, with the spheres described above, no such torque can exist. (As a matter of fact, the absence of any observable torque on the rotor in the presence of a strong rotating magnetic field is a good test for the excellence of the material.) As a result, new methods of accelerating the rotor were developed.

The Air-Jet Drive

The first method tried employed air jets which impinged directly on the rotor during the evacuation process. The air was allowed to leak into the vacuum chamber through the directed jets until the rotor reached the desired running speed. The jets were then sealed and the chamber quickly evacuated.

In preliminary experiments with this method, the rotor was driven to about 150 rps and allowed to coast while observations were made on its axis of rotation. Two types of observations were carried out. First the initial axis of rotation was made vertical and the rotation of the earth observed. The observations extended over an hour and, within the limits of the optical methods employed, the axis of rotation of the sphere remained fixed, i.e., it rotated as it should have with respect to the vertical.

The second set of experiments was carried out with the axis of the rotor aligned with that of the earth's rotation. Under these conditions, the axis of the rotor remained parallel to the axis of the earth for approximately an hour within the observational limits. The direction of the axis of rotation was determined by observing a small fiducial mark on the rotor through a cathetometer telescope in the light of a strobatack. This is not a precise method of observation and is limited in accuracy to about three minutes of arc. The above observations extended for an hour or less. The pumps were not able to produce the desired vacuum quickly enough to prevent appreciable deceleration of the rotor over periods greater than an hour since both the rotor and the plastic vacuum chamber necessarily had to be out-gased. Also, the non-homogeneity of the rotor became troublesome at low rotor speeds.

The Electron Drive

In order to avoid the above difficulties, new methods of accelerating the rotor were investigated. In Fig. 6 is shown a schematic diagram of a method of driving the rotor by electron impact. The vacuum chamber is made of glass and is evacuated to less than 10^{-5} mm of mercury. The rotor is magnetically suspended and electrons from the electron gun are directed tangentially on the periphery of the spherical rotor. In preliminary experiments, a beam of one milliampere, 1500-volt electrons was deflected by the deflecting plates so that after being bent by the axial magnetic field of the solenoid, they struck tangentially on the spherical rotor.

In the first experiment the rotor was covered with a thin coating of willemite so that the spot where the electrons impinged might be observed. However, after proper adjustment this was not necessary. With this arrangement, accelerations of the order of one-half rps per minute were obtained with a three-quarter-inch rotor. This is too slow for practical use but by increasing the accelerating potential to 20,000 volts and the current to several milliamperes the method might be used in practice.

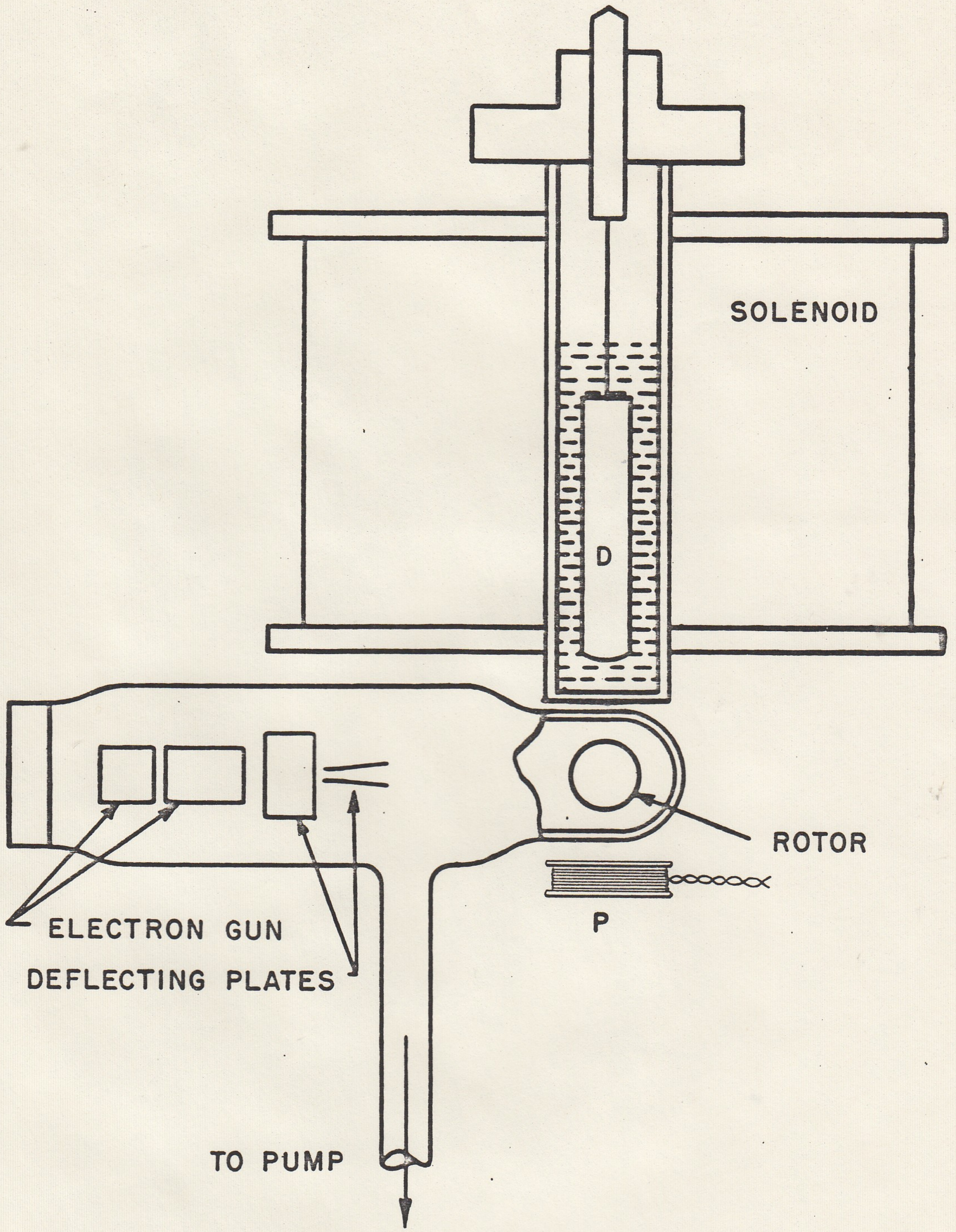

Fig. 6 APPARATUS USED TO DRIVE ROTOR WITH ELECTRON STREAM

It might seem that the rotor would charge negatively and repel the electron beam. However, this is not the case because of the secondary electrons knocked out of the rotor. These are collected by a grounded electrode in the side of the chamber (not shown in the figure). It is clear that this method has an advantage over the air drive because the system may be out-gased, sealed off and used without pumps.

The Hydrogen-Jet Drive

If a palladium tube, or "window", is heated, hydrogen (but no other gas) passes through it freely. Hence, hydrogen may be made to pass into a chamber through jets, a second such window providing an exhaust. This principle was used to develop a hydrogen-jet drive in which the hydrogen stream strikes the rotor after being admitted through palladium to tubes which form the jets. Since the gas escapes through the second window in the chamber the need for rapid pumping is eliminated. Accelerations of one rps per two minutes have been obtained by this method but it has not been sufficiently explored to determine whether or not it is practicable.

V. FRICTION-FREE HORIZONTAL BEARINGS

The small frictional effects observed when the axis of rotation of the sphere is as large as 90 degrees with the axis of the magnetic field suggests the use of horizontal friction-free bearings for supporting rotors spinning around a horizontal axis. In Fig. 7 is shown a schematic sketch of such an arrangement. The magnetically supported spheres are made of the powdered molybdenum permalloy composition described above and are precisely ground. They are connected by a non-conducting, non-magnetic rod. The rotor, G, is driven to the desired speed by air jets N_1 and N_2 (Fig. 7). When

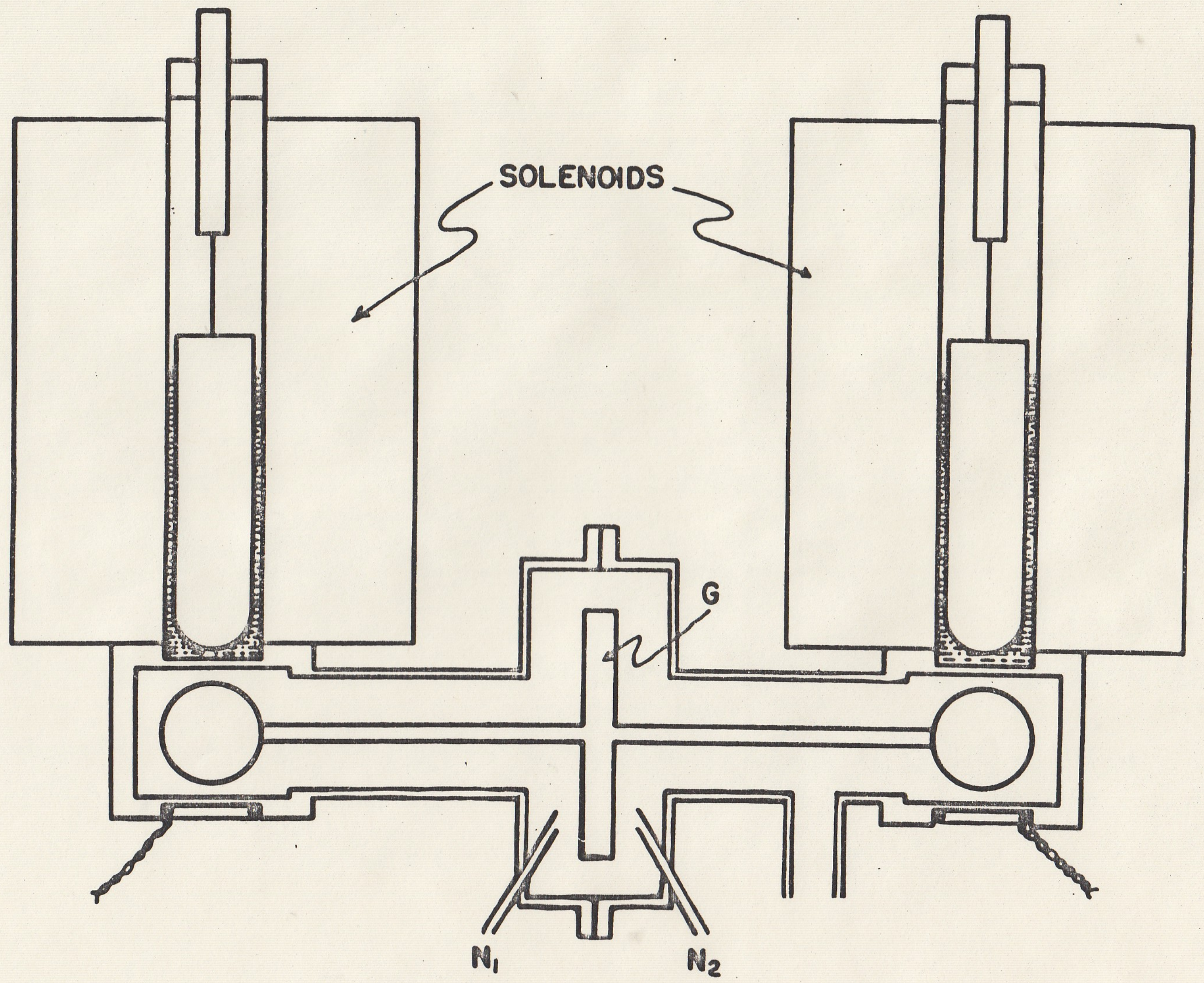

Fig. 7 FRICTION-FREE BEARINGS SPINNING AROUND A HORIZONTAL AXIS

the rotor reaches full speed, N_1 and N_2 are sealed off and the rotor is allowed to coast. The observed deceleration is accounted for entirely by air friction on the rotating parts. Since measurements show that the chatter in these bearings is of the same order of magnitude as the natural Brownian motion, or fluctuations, these bearings should make ideal gyroscope gymbals.

Figure 8 is a photograph of the apparatus with the vacuum chamber in place and Fig. 9 is a photograph of the apparatus with the vacuum chamber removed. The use of such bearings is being further investigated.

VI. CONCLUSIONS

At the moment there appear to be two ways of converting the magnetically-supported gyroscope into a practical instrument:

1. The gyroscope might be mounted on a platform which is "servoed" by a less precise one in such a way that the axis of the solenoid is always in the direction of the acceleration.

2. Three, or preferably more, solenoids might be used, spaced at intervals around the solid angle for supporting the spinning spherical gyroscope so that rotor position with respect to the solenoids remains approximately fixed regardless of the acceleration of the vehicle. This latter method is in the developmental stage but as yet has not been completely perfected.

In both of these approaches the circuits and solenoids must be completely revised to give greater strength and practicability. Also, permanent magnets might be used to support part of the load.

The fact that the magnetic support has no chatter above the order of magnitude of the natural or Brownian fluctuations, makes it an almost ideal gyroscope bearing. However, a great deal of development must be carried out before the apparatus can be made practical. Certainly a better rotor material than that discussed

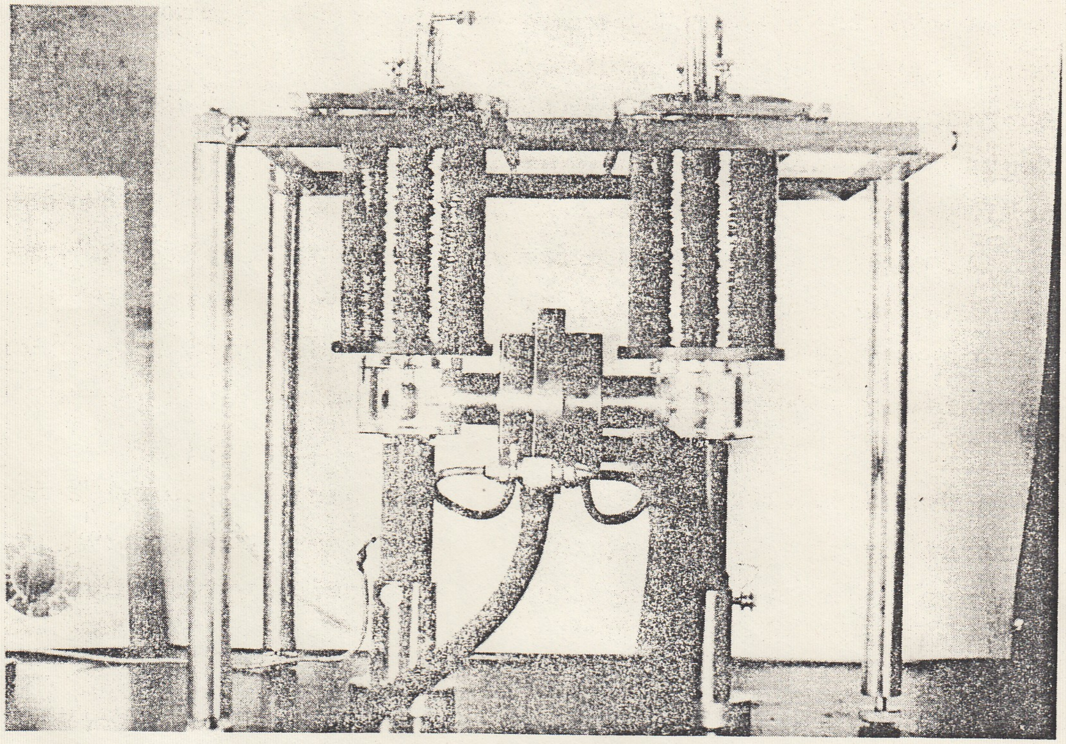

Fig. 8 HORIZONTAL BEARINGS WITH VACUUM CHAMBER IN PLACE

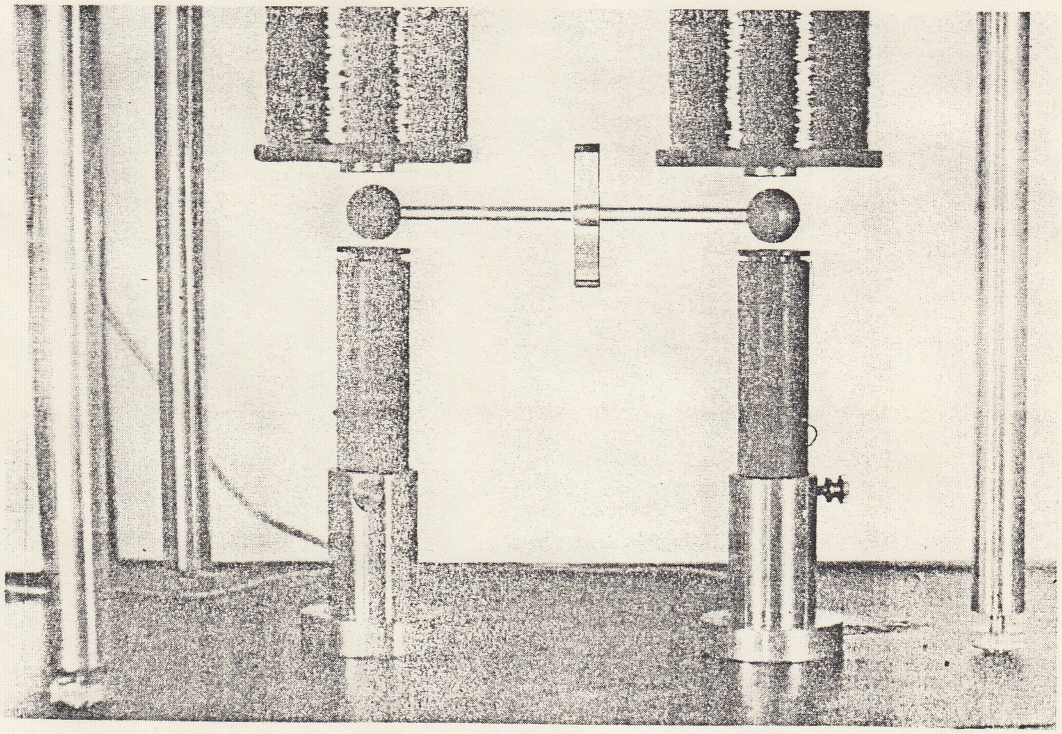

Fig. 9 HORIZONTAL BEARINGS WITH VACUUM CHAMBER REMOVED

above must be found. It is too weak mechanically to permit high rotor speeds and has not yet been made homogeneous enough for accurate performance. Also, it is desirable that the magnetic-memory effect be further reduced. However, this rotor problem does not appear to be an impossible one. The pick-off problem must also be solved but this too seems to be a straight-forward developmental one.

Thus, the above apparatus in its present state is strictly a laboratory design for laboratory experiments. It is not suitable for field use such as on a guided missile where accelerations in all directions take place.

In conclusion the investigation showed that, although a vast amount of development remains to be carried out, the magnetically-suspended spherical gyroscope has great promise as a free gyroscope.

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