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Spinning Rotor Pressure Gauge*

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A magnetically suspended rotor pressure gauge is described for measuring pressures below 10^{-4} torr. The data are in good agreement with those obtained with a calibrated Alpert ionization gauge over the range 10^{-4} to 5×10^{-8} torr. When the gas in the vacuum system was frozen out with liquid helium, the rotor gauge recorded a residual pressure of about 5×10^{-10} torr. A brief discussion is given of a number of effects which unless eliminated may introduce errors into the measurements at the lowest pressures.

In the process of measuring the pressure in a vacuum system, it is often important to avoid the introduction of high speed electrons and ions, hot filaments, and other surfaces which may produce contamination. Also, in many cases, it is essential that the pressure gauge does not change the composition of the gas, or introduce or remove gas from the system. The purpose of this paper is to describe a high vacuum gauge which, essentially, is free of the above difficulties and at the same time is capable of giving absolute values of the pressure when the composition of the gas is known. The principle of the method is old,[1] but has been made useable for this purpose by the development of the magnetic suspension.[2] It consists in determining the frictional torque produced by the gas or vapor on a spinning rotor. The rotor is magnetically suspended inside of the vacuum chamber and spun to the desired speed. It is then allowed to coast freely and its deceleration measured. If the friction introduced by the magnetic support is negligible in comparison with the gaseous friction and if the mean free path of the molecules is longer than the dimensions of the chamber surrounding the rotor, then for the case of a spherical rotor, it can be shown that the pressure p in dynes/cm^2 is given by the relation

$$p=\frac{rd}{5C(t-t_0)}\left(\frac{2\pi RT}{M}\right)^{\frac{1}{2}}\log_e\frac{N}{N_0}, \tag{1}$$

where N_0 is the number of rev/sec at the time t_0, N is the number of rev/sec at time t, r is the radius of the rotor in cm, d is the density of the rotor material, T is the absolute temperature, M is the molecular weight of the gas, R is the gas constant, and C is a constant which turns out to be approximately unity for a polycrystalline rotor surface.[1,3] If the rotor is a solid right circular cylinder,

$$p=\frac{rd}{2C(t-t_0)}\left(\frac{2\pi RT}{M}\right)^{\frac{1}{2}}\left(\frac{1}{2+r/h}\right)\log_e\frac{N}{N_0},$$

where r is the radius and h the length of the cylinder.

The apparatus is shown schematically in Fig. 1. The rotor, which is made of a ferromagnetic material which can

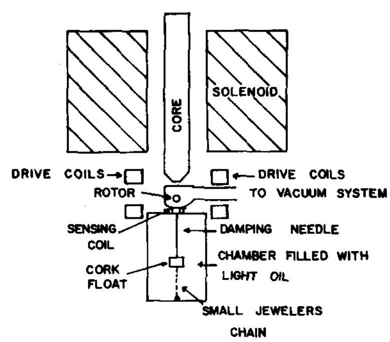

Fig. 1. Schematic diagram of rotor gauge.

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[1] S. Dushman, *Scientific Foundations of High Vacuum Technique* (John Wiley & Sons, Inc., New York, 1949).

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[3] M. Knudsen, *Kinetic Theory of Gases* (Methuen and Company, London, 1946), second edition.

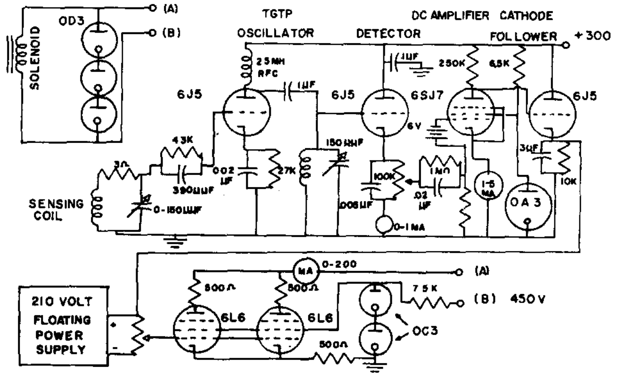

FIG. 2. Diagram of support circuit.

be baked out effectively such as steel, magnetic stainless steel, or nickel, is freely suspended inside of a glass vacuum chamber by the axial magnetic field of the solenoid. The solenoid is mounted above the vacuum chamber and produces a magnetic field which is symmetrical with respect to a vertical axis and is diverging downward in the region where the rotor is suspended. The rotor is maintained at a definite height by an automatic regulation of the current in the solenoid while its horizontal position, which is along the axis, is determined by the shape of the axial magnetic field. Figure 2 shows one of a number of different circuits that have been used for automatically regulating the current in the solenoid. A small coil mounted either above or below the vacuum chamber serves as a convenient sensing element for the servo circuit of Fig. 2 which regulates the current through the solenoid in such a way that the rotor is maintained at the desired height in the vacuum chamber. Although the rotor automatically seeks the strongest part of the magnetic field at a given vertical position which is on the axis, if disturbed it will oscillate around the axis and means should be provided for damping out this type of motion. For small rotors, this is accomplished by mounting a small steel needle in a tube of liquid just below the vacuum chamber as shown in Fig. 1. If the rotor moves, the needle will follow the horizontal motion and damp it out. For rotors larger than 0.2 in. in diameter it is usually more convenient to hang the ferromagnetic core (usually iron) of the solenoid by a fine wire as a pendulum in a dash pot of oil. This also is very effective in damping horizontal rotor motion.[2] When the proper adjustments are made, no movements of the rotor either vertical or horizontal can be observed with a microscope focused on the fine scratches on the rotor.

The size of the support solenoid is, of course, determined by the size of the rotor used. From Eq. (1) it will be observed that the precision with which a pressure can be measured is determined essentially by $r\Delta N/N$. Since rotors made of the same material and having the same shape explode at about the same value[2] of $2\pi rN$, the precision of the method in practice does not depend critically upon the size of the rotor used. Although we have used rotors varying in diameter from 2–0.001 in. in some experiments, we have found rotor diameters between $\frac{1}{8}$ and $\frac{1}{64}$ in. convenient sizes. For such rotors, the solenoid contains approximately 25 000 turns of No. 28 enameled copper wire wound on a plastic frame. It is also supported by nonmagnetic nonconducting material. Its direct current resistance is about 1000 ohms and its inductance about 20 h. The sensing or pick-up coil consists of from 10–50 turns of No. 40 wire bunch wound with an inside diameter from 0.1 to about 2 cm depending upon the diameter of the rotor. This sensing coil is in the grid circuit of a partially neutralized tuned-grid, tuned-plate oscillator which operates at from 3–8 Mc. A vertical movement of the rotor with respect to the sensing coil changes the Q of the oscillator circuit and hence the amplitude of the oscillations. The output of the oscillator is applied to the grid of a 6J5 which serves as an infinite impedance detector stage. The dc potential across the cathode resistor is proportional to the amplitude of the oscillations and serves as an electrical measure of the rotor height above the sensing coil. This dc signal is amplified and used to control the current through the solenoid. In order to prevent vertical oscillations of the rotor a phase lead, together with effective damping or "antihunt" in addition to the original signal, is introduced into the amplifier stage. The rotors are spun inside of the vacuum chamber by a rotating magnetic field in a manner similar to that of the armature of an induction motor or of a synchronous motor. Any standard drive circuit may be used for the motor drive.[2]

The rotors used were either solid spheres or solid right circular cylinders. Carefully selected uniform ball bearing balls were found to serve as excellent rotors. The solid cylinders were accurately made of high strength steel and the ratios of their lengths to radii were slightly less than $\sqrt{3}$ in order to insure rotational stability. The rotors were carefully demagnetized before introducing them into the field of the solenoid.

Figure 3 shows a schematic diagram of the method used for measuring the rotor speed. Light, after passing through a dilute water solution of $CuSO_4$ to remove the infrared, falls symmetrically on the rotor which reflects or scatters light into a photomultiplier tube. Since all rotor surfaces have some nonuniformity in their optical properties, the photomultiplier tube generates a signal equal in frequency to the rotor speed. The signal from the photomultiplier is fed into a high gain preamplifier which serves as a peak clipper and harmonic generator, then processed by a dual frequency-conversion system in which the speed signal is mixed with the appropriate component of the spectrum obtained from a multivibrator locked to a secondary crystal-controlled frequency standard. The resulting difference-frequency signal is amplified and mixed with the output of a calibrated interpolation oscillator which is adjusted so

TABLE I.

Ionization gauge (torr)	Rotating sphere (torr)
10^{-4}	9.0×10^{-5}
2×10^{-5}	1.6×10^{-5}
2×10^{-6}	1.7×10^{-6}
2×10^{-7}	1.5×10^{-7}
5×10^{-8}	$4\ \times10^{-8}$

that the frequency of this difference-frequency signal is zero. Since the order of the harmonic being used is known, the frequency of the speed signal is determined to an accuracy limited only by the accuracy of the interpolation oscillator. The drift in frequency of the interpolation oscillator was less than 10^{-2} cycles/day. The deceleration is measured by determining the time required for the speed signal to change in frequency by some small amount. Time measurements are made with a calibrated stopwach.

The process of measuring the small values of deceleration which are obtained at very low pressures can be expedited by measuring frequency changes of harmonics of the rotor speed signal. Thus, a change of 1 cps in the actual speed of the rotor becomes a change of 50 cps in the frequency of the 50th harmonic, for example. It has been found that an average signal from the photomultiplier generates at least 70 useable harmonics. No accuracy in measurement is lost in this method since the major source of error is that in the interpolation oscillator, clearly independent of the order of the harmonic being measured. At the lowest pressures, the rotor is driven at speeds as high as possible without producing plastic flow in the rotor. Equation (1) shows that the pressure measurement depends on rotor speed only through the ratio of dN/dt to N. Thus, the measurements obtained at any harmonic of the rotor speed signal are the same as those which would be obtained if the speed signal frequency were actually that of the harmonic being measured.

In order to test the theory of the gauge, the glass chamber surrounding the rotor was attached to a vacuum system, the pressure in which was measured by a calibrated Alpert-type ionization gauge. The system was connected to the pumping system through a glass copper foil trap immersed in liquid nitrogen. The pumps and traps could be isolated by cut-off valves. The pumping system consisted of an oil diffusion pump backed by a rotary oil pump. For some of the experiments, a Vac-ion pump was used. A very thin, semitransparent, slightly conducting, uniform film of gold was evaporated on the inner surface of the glass chamber surrounding the rotor in order to eliminate the effect of electrostatic charges on the chamber. This coating was not conducting enough to appreciably affect the action of the sensing coil. The vacuum system, including the ionization gauge, the rotor, and its surrounding chamber was baked out for one day at 400°C. Table I shows typical values obtained over the range 10^{-4} to 5×10^{-8} torr. Below

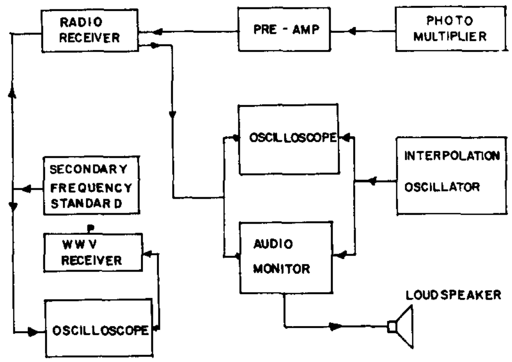

FIG. 3. Schematic diagram of method of measuring rotor speed.

10^{-8} torr, the ionization gauge gave erratic readings, but in general gave pressures below those observed with the rotating sphere. It is well known that the ionization gauge may become unreliable in this region, but the results also may be accounted for by friction other than gaseous friction possible in the magnetic bearing. For this reason, it was decided to abandon the ionization gauge and to remove the gas from the rotor chamber with a liquid helium pumping system. In this way, it should be possible to set an upper limit to the friction in the magnetic bearing. The entire system containing the rotor chamber was made of an aluminum silicate glass (Corning No. 1720) which is much more impervious to helium than Pyrex. The rotor chamber, after being covered inside with the thin film of gold, was sealed to a tubular glass finger which could be immersed to at least 12 in. in liquid helium. The diameter of the finger and connections to the rotor chamber were approximately the same as the diameter of the chamber. This system was first evacuated by a mercury diffusion pump through nitrogen cold traps, then baked out for a day at 400°C and sealed off. The rotor chamber was next mounted below the solenoid and the pressure measured by the deceleration of the sphere. The long finger was then immersed in liquid helium and, after some hours, the pressure was again measured with the rotating sphere. With this procedure, when the precautions to be described below were taken, the measured pressure was about 5×10^{-10} torr if the residual gas was air. This assumes that the value of C in Eq. (1) was constant and equal to one, also that all of the rotor friction was due to gaseous friction which, of course, may not have been the case.

If a symmetrical homogeneous rotor, such as a sphere or cylinder, is magnetically suspended by a symmetrical axial magnetic field and if the axis of the field and the axis of spin are the same and are vertical, then rotation of the rotor does not change the flux through the rotor. As a result, no frictional torque due to the support should be observed. However, this ideal situation probably cannot be realized in practice. Consequently, we have made studies of the various factors which may introduce friction into the suspension. It might seem that unavoidable small stray magnetic fields, the earth's field, etc. would produce a component of the magnetic field perpendicular to the axis of spin and consequently introduce friction. A little consideration shows that, due to the relatively high permeability of the rotor and solenoid core and to their proximity, the rotor "hangs like a pendulum" along the resultant of the magnetic field. This resultant, therefore, is parallel to the gravitational field. If, now, the homogeneous rotor is spun rapidly, its axis of rotation automatically will, after a short time, pass practically through the center of permeability with the axis of spin along the vertical resultant of the field. Consequently, the effects due to very small magnetic fields other than the solenoid are very minute, as long as they are steady. For example, the earth's field was carefully compensated by large Helmholtz coils before mounting the solenoid in place without noticeable changes in friction. On the other hand, changing magnetic fields perpendicular to the axis will, of course, produce drag. Another possible source of friction results from the fact that the rotor should act like a gyroscope. The direction of the axis of the rotor would tend to remain fixed in space. Consequently, the rotation of the earth produces a torque which in turn would induce a precession of the rotor axis around the vertical. This can be shown to induce eddy currents in the rotor and cause it to decelerate. The effect can be estimated for "soft" ferromagnetic material and comes out to be larger than observed. This probably results from the fact that the steel is so hard magnetically that the axis of spin is "locked" into the axis of the magnetic field; i.e., it is like locking a gyroscope in its gimbals. The rotors were carefully demagnetized before using in order to eliminate stray poles. The fact that the center of permeability is above the center-of-mass also reduces the precession effect. With rotors made of materials such as Permalloy powder imbedded in plastic, we have observed the gyroscopic precessions due to the rotation of the earth. Another effect which may produce rotor deceleration is the presence of electrostatic charges on the walls of the rotor chamber and on the rotor. This effect can be troublesome with glass chambers, but fortunately, it was eliminated by the thin uniformly conducting gold coating over the inner surface of the rotor chamber which served as a Faraday cage. It is necessary, of course, to maintain the temperature of the rotor constant during the deceleration measurements. While the rotor is being accelerated it is heated by the eddy currents due to the drive. Consequently, when it is allowed to coast, it loses heat to its surroundings and cools. As a result, the rotor contracts. This, in turn, decreases the moment of inertia and speeds up the rotor in order to maintain the angular momentum constant. Consequently, it was always necessary when the pressure was below 10^{-7} torr to allow the rotor to spin for several hours until it reached the temperature of its surroundings as shown by extrapolation of deceleration versus time curves before deceleration readings could be made with reliability. For example, if the temperature of a 0.4-mm steel sphere spinning at 10^6 rps is decreased by 1°C it will speed up about 20 rps. It is necessary to maintain the temperature of the surroundings of the rotor to about 0.01°C when measuring the lowest pressures. One of the most troublesome effects is that introduced by mechanical vibrations in the solenoid mounting induced by building vibrations. Such vibrations produce flux changes through the rotor in such a way as to introduce damping friction into the spinning rotor; i.e., a rapidly spinning rotor will lose several rps if a door is slammed in the next room. In order to eliminate this type of rotor damping, it was essential not only to shock mount the vacuum system, the solenoid mounting, the electronic equipment, etc. with air and sponge rubber cushions, but also to make the lowest pressure measurements between 1 and 6 A.M., at times when there was no other activity in the laboratory or in its immediate surroundings. It was also found essential to maintain the rotor at the same vertical position during the measurements. This was accomplished in two ways; first, maintaining the current through the solenoid constant and second, keeping the height constant by observing the rotor with a telescope. A permanent change in height in the rotor may produce either an acceleration or a deceleration of the rotor. A good servo circuit will regulate the current through the solenoid so that the pull of the solenoid on the rotor balances the gravitational pull to at least one part in 10^5. The time constant of the circuit is usually the order of 10^{-3} sec so that the rotor moves vertically less than 10^{-8} cm or about one atomic diameter before being brought back to its original position. The pressure of the light on the rotor may produce acceleration or deceleration unless it falls symmetrically on the rotor. It was, therefore, necessary to make sure that the light spot was carefully positioned on the rotor. An extra precaution of spinning the rotor first clockwise and then counter-clockwise checks the absence of this effect. It was also necessary to keep the intensity of the light as low and as constant as possible since, at best, it always gave some heat energy to the rotor. Possible accelerations or decelerations of the rotor due to the alternating current in the sensing coil were investigated and found to be too small to observe. The current in the sensing coil was always made very small to prevent appreciable heating of the rotor or chamber. Several other effects including stretching of the rotor by the mechanical forces, creep in the rotor, and thermal fluctuations in the rotor or system were investigated, but they turned out to be too small to affect the results. In some of the experiments, a light beam photoelectron multiplier sensing device was used instead of the sensing coil. This system was satisfactory but was more sensitive to mechanical vibrations.

Recently, Keith and Kenney[4] have concluded from calculations based upon the Birkhoff theory of relativity that a spinning symmetrical sphere or rod will radiate gravitational energy. If this is the case, it would produce a deceleration of the rotor. They estimate that this gravitational radiation will produce a deceleration of the rotor equal to that caused by air friction on the rotor at pressures between 10^{-9} and 10^{-10} torr provided the rotor spins at 10^6 rps. On the other hand, according to Echols,[5] gravitational radiation effects calculated either by the Birkhoff or the Einstein relativity theory would be much less than the above and far too small to observe in our experiments. The present measurements are not sensitive enough to detect this effect, but an attempt will be made to improve our vacuum system and other experimental conditions with the view of possibly distinguishing between the above theoretical predictions as well as extending the useful range of the gauge to lower pressures.

We are much indebted to J. A. Keith, D. J. Kenney, and R. Echols for informing us of their theoretical conclusions.

[4] J. A. Keith and D. J. Kenney, Research Institute of Science and Engineering, University of Detroit Report I; and private communication.
[5] R. Echols (private communication).

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Tunnel Diode Hydrostatic Pressure Transducer

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A very sensitive hydrostatic pressure transducer was made using a silicon tunnel diode. The transducer consists, essentially, of a tunnel diode shunted by a resistor which satisfies the stability conditions for operation in the amplifier mode. The advantages of the tunnel diode transducers are (1) small size, (2) sensitivity, and (3) versatility. Since the p-n junction region is normally 1 mil in diameter or less, miniaturization is possible. Pressure sensitivities as high as 2 mv/v/psi were observed over a 60-psi pressure range. Expressed in terms of gauge factor, the above sensitivity is equal to about 30 000. Such high sensitivities, within narrow pressure ranges, were achieved at pressures up to 20 000 psi. The pressure range as well as the pressure sensitivity in a chosen pressure interval can be varied very simply by adjusting the values of the shunt resistor and the current through the diode-resistor combination. Even higher gauge factors can be obtained with other semiconductor materials.

I. INTRODUCTION

FOR the last two years Esaki or tunnel diodes have been a subject of very intensive research and development effort in a large number of laboratories all over the world. A multitude of papers have appeared in the literature on the subject of applications of tunnel diodes. The field of pressure effects on the characteristics of diodes seems to have been somewhat neglected, however.

Outside of the Bell System only two groups of workers are known to the authors to have reported their findings on the above subject.[1,2] At the Laboratories, W. P. Mason and W. G. Pfann have considered the possibility of using tunnel diodes as hydrostatic pressure transducers. Subsequently, a study was made by J. J. Forst on the effect of pressure on a Ge tunnel diode.[3] This latter work prompted our investigation, the results of which are the subject of this report.

The approach proposed here is to operate the tunnel diode in the amplifier, or oscillator mode, rather than in the switching mode.

The switching mode of operation is outlined in Sec. II, stability criteria for amplifier mode are given in III, and the amplifier mode method is described in IV. Sections V–VII are devoted to the experimental setup, results, and applications, respectively. Discussion of obtainable sensitivities to pressure is given in Sec. VIII. Finally, the method used to display true I–V characteristics of diodes is briefly described in the Appendix.

[1] L. Esaki and Y. Miyahara, Solid State Electronics 1, 13 (1960).
[2] S. L. Miller, M. I. Nathan, and A. C. Smith, Phys. Rev. Letters 4, 60 (1960).
[3] J. J. Forst (unpublished).

II. TUNNEL DIODE IN THE SWITCHING MODE

We will assume that a Ge tunnel diode is biased at point A of its I–V characteristic (I) as shown in Fig. 1. Curve (I) corresponds to the data at atmospheric pressure and curve (II) to the characteristic at a pressure of, say, 10 000 psi. If the current is kept at a constant value I_b while the pressure is increased from atmospheric to 10 000 psi, the operating point will shift from A to B. The corresponding voltage change will be $\Delta V_{AB}=V_B-V_A$, where V_B and V_A are voltages that correspond to points A and B on the I–V characteristic. This is equivalent to saying that the resistance of the diode has increased from a value $R_A=V_A/I_b$ at point A to $R_B=V_B/I_b$ at point B.

It is apparent from Fig. 1 that the voltage change ΔV_{AB}, which corresponds to a given increment in pressure, increases with bias current. The limiting value of the bias