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POTENTIALS ON ROTOR SURFACES*

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(Received 1 August 1968)

A small radial electrical potential gradient has been observed to exist across a Duraluminum rotor spinning at high speed in air at pressures from 10^{-5} to 10^{-6} Torr.

Several investigators have searched without success for axial potential gradients produced in metal spinning rotors. Lodge[1] and Nichols[2] looked for the effect in metal discs spinning in air at atmospheric pressure, but the comparatively large and variable electromotive forces introduced by the rubbing electrical contacts on the axis and on the periphery made their results inconclusive. More recently Freedman[3] and his associates also were unable to find the phenomenon with more reliable equipment. In this paper, experiments are described in which a small radial potential difference is observed across a rapidly spinning Duraluminum (ST14) rotor surrounded by air at pressures between 10^{-5} and 10^{-6} Torr. Robl,[4] Schiff and Barnhill,[5] Dessler, Michel, Rorschach, and Trammell,[6] and Herring[7] have shown theoretically that a gravitationally induced electrical field should exist outside of a vertical conductor. In a most ingenious experiment, Witteborn and Fairbank[8] have recorded a vertical field of 5.6×10^{-11} V/m inside of a copper cylinder, a result which is in agreement with the theory of Schiff and Barnhill. Since centrifugal fields can be made very much largen than the earth's gravitational field, the effect should be correspondingly larger in a rapidly spinning rotor.[9]

Figure 1(a) shows a schematic diagram of the experiment. The rotor R was spun inside the evacuated metal chamber V by an air-supported, air-driven turbine T situated below V. The thin flexible shaft S which connects the turbine to the rotor passes through the electrically insulated vacuum-tight oil glands G_1 and G_2. This scheme for supporting and driving high-speed rotors in a vacuum has been previously described; so the mechanical details will not be given.[10] Electrical connection with the rotor was made through a water-cooled liquid-mercury contact with the shaft at M. The rotor, the vacuum chamber, bearings, turbine, etc. were all nonferromagnetic. This simplified the compensation of the earth's magnetic field at the rotor by a large Helmholtz coil which surrounded the apparatus. The turbine drive was so designed that the direction of rotation could be reversed. The vacuum chamber and the electrical and oil shields were made of metal and were grounded. Figures 1(a) and 1(b) show a schematic cross section (not to scale) and top view of the rotor which is machined in the form of a cross. The rotors were 15 cm in diameter and 2 cm thick, and the cross arms were 2 cm wide. The rotating parts were electrically insulated from the stationary parts by vacuum-pump oil and neoprene O rings in G_1 and G_2 and the Bakelite-supported air cushion H beneath the turbine. A thin, light metal disc D insured that the small quantity of vacuum-pump oil leaking through G_1 could not reach the rotor. The chamber V was evacuated by an oil diffusion pump and forepump through a liquid-nitrogen trap. Variable emf's generated in the liquid-mercury contact with the shaft at first gave considerable trouble, but the problem was finally solved by using a very small needle of copper or

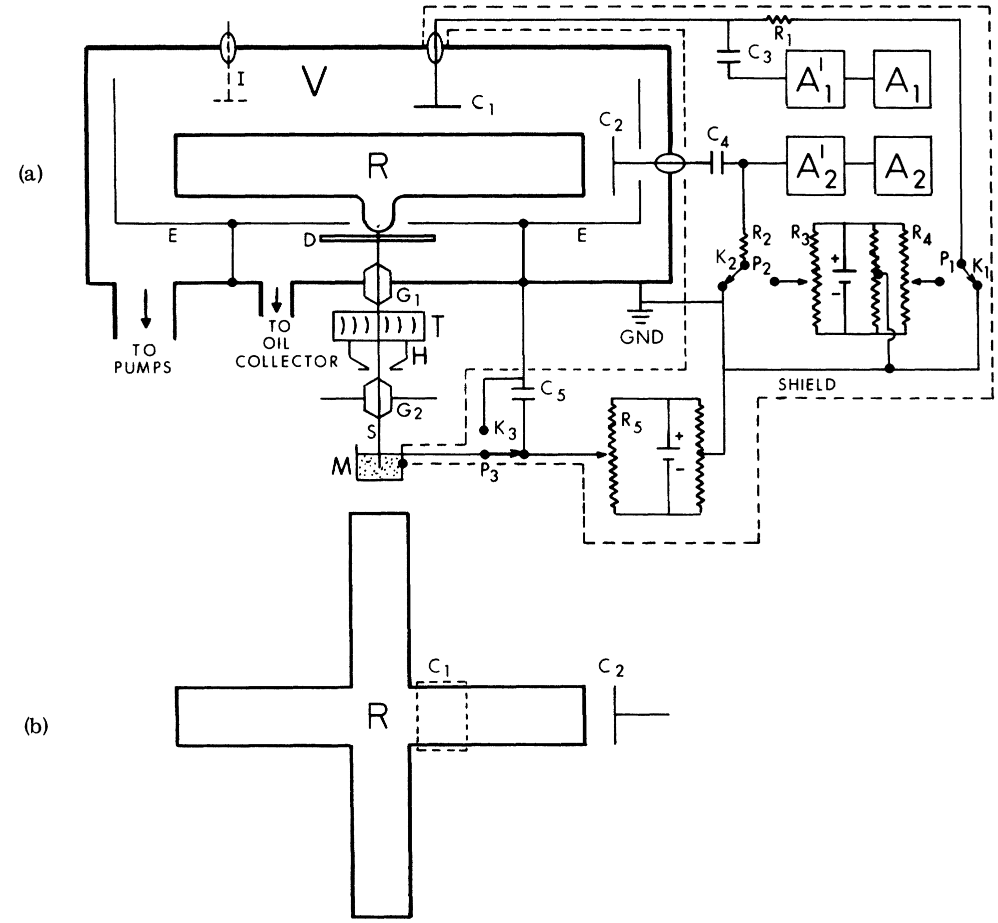

FIG. 1. (a) Schematic cross section of experimental apparatus. (b) Top view of the rotor.

of steel for making contact between the shaft and mercury and by making the thick-walled cup which held the mercury from copper and surrounding it by rapidly flowing cooling liquid. It was found necessary to keep the mercury free of oil. With this arrangement the emf's became sufficiently steady. In some of the experiments the shaft S was made of stainless steel and the needle of copper, but it was found that they could be replaced by a steel shaft and steel needle without appreciable change in the magnetically induced emf. In all cases, any variation of the potential of the rotor was immediately observed and measured.

The metal capacity pickups C_1 and C_2 were mounted on metal rods which passed through insulating bushings in V. C_2 was stationary, while C_1 could be moved from axis to periphery while V was evacuated, with the rotor spinning or at rest. The electrical potential on C_1 and on C_2 could be varied by the movable electrical contacts on the resistances R_3 and R_4, while the potential on the rotor could be varied by moving a contact along R_5. The capacitors C_3, C_4, and C_5 each were 0.4 μF and allowed the electrical pulses to pass through while insulating the dc. The resistances R_1 and R_2 were wire wound and 3×10^5 Ω. The switches K_1, K_2, and K_3 permitted the connection of P_1, P_2, and P_3 directly to a common ground when desired. The potentials at P_1, P_2, and P_3 were measured by potentiometers with a precision of 10^{-6} V. It will be observed that if the potential of the surface of the rotor differs from P_1 and P_2, a charge will be induced upon C_1 and C_2 as each arm of the rotor passes the stationary plates of C_1 and C_2. These induced charges produce electrical signals which are amplified by the amplifiers $A_1'A_1$ and $A_2'A_2$. Since the respective rotor surfaces serve as plates of the condensers C_1 and C_2, when the potentials on the other plates approach the same value as that of the moving rotor surfaces the amplified signals will pass through a minimum or change sign. Consequently, the difference in potential between the rotor surfaces at C_1 and at C_2 can be measured. In most of the experiments P_1 and P_2 were connected directly to the metal vacuum chamber V, which also was the common ground, and the potential on the rotor slowly varied. The pulse shape changes with rotor speed and radial position of the pickup C_1, but the time constants are such that this does not appreciably effect the potential at the minimum. A potential change of a few microvolts between the axis and periphery of the rotor could be detected.

An axial magnetic field induces a radial emf in the rotor equal to $\frac{1}{2}R^2\omega B$, where R is the radius of the rotor, ω is the angular speed and B the value of the magnetic field. Large Helmholtz coils were used to compensate for the earth's magnetic field. Also these coils were used to induce electrical potentials both positive and negative across the spinning rotor which were used for checks and calibration of the measuring system. The direction of the potentials induced by the magnetic field was reversed by reversing the direction of the spin of the rotor. In most of the experiments the earth's magnetic field was so well compensated by the field of the Helmholtz coils that the potentials induced by the magnetic field became negligible in comparison to the other potentials observed.

Most of the experiments were made with rotors composed of forged Duraluminum ST14. A few qualitative experiments were made with titanium[11] 6ALHV and nonmagnetic stainless steel 24. Unfortunately, it was necessary to use metal alloys instead of pure metals in order to obtain the desired high rotational speeds without plastic flow. The rotors were carefully cleaned before mounting in the vacuum chamber but no attempt was made to out-gas the rotor because the mechanical properties of the alloys used are changed by heating to the necessary temperatures. Also the rotors were in contact with vapors from low-vapor-pressure vacuum-pump oil but were carefully shielded from the liquid oil. The pressures surrounding the rotor were varied from 10^{-4} to 10^{-6} Torr. Consequently, the rotor surfaces were never free of absorbed gases and vapors, oxides, etc. It was found that the potential of the spinning rotor surface changed when it was heated well above room temperature and when it was bombarded by ions from an electrical discharge from I to the spinning rotor both in air and in helium at reduced pressure. This probably was due to changes in the contamination of the surface. In fact, the experiment turned out to be a very sensitive method of measuring what appeared to be small changes in surface contamination.

It was found that the electrical potential of the rotor surface at a given radial distance remained constant for long periods of time if the rotor speed and temperature were held constant. On the other hand, if the rotor speed was increased, the electrical potential of the periphery became slightly positive with respect to the axis. When the rotor speed was then reduced to its original value, the potentials of the rotor surfaces returned to approximately their original magnitudes. For a given experiment, this radial potential change across the rotor was roughly proportional to the square of the rotor speed. Considerable scatter in the values was obtained in different experiments. However, with a change in rotor speed from 100 to 650 rps the potential changes observed were of the order of 1 mV and hence were much larger than the sensitivity of the apparatus. The results obtained were independent of the direction of rotation when the earth's field was carefully compensated. The values obtained with the titanium and stainless-steel rotors differed in magnitude but not in sign from those obtained with the Duraluminum rotors. The above observed results are in reasonable agreement with the theory of Dessler et al.,[6] if the following somewhat uncertain factors are small. It is clear that the relative speed of the rotor surface at the periphery and the colliding molecules of the residual gas increased with increase of rotor speed. On the other hand this is not the case on the axis. At 650 rps the peripheral speed was 3.3×10^4 cm/sec. Consequently, at least part of the observed effect might possibly have been due to changes in the absorbed gases, etc., caused by the more energetic molecular bombardment on the periphery at the higher rotor speed. However, the same potentials were observed when the rotors were rapidly or slowly accelerated or decelerated, i.e., equilibrium was reached very quickly. Furthermore, the potentials at the periphery of the four arms of the rotor usually differed slightly. This was observable on an oscilloscope especially at the "minimum" and found not to change appreciably with the rotor speed. Also, the results were essentially independent of the gas pressure (10^{-5} to 10^{-6} Torr) surrounding the rotor as long as the rotor temperature was not changed appreciably during the experiment. Consequently, it seems unlikely that this phenomenon would account for the magnitude of the observations. A thermoelectric effect generated by a radial thermal gradient in the rotor could change the potential from axis to periphery. A small radial temperature gradient exists because of the greater gas friction on the periphery but both the observed and calculated values for this temperature gradient were much too small to produce an appreciable thermoelectric effect. Another phenomenon which may produce electrical potential gradients along the surface of a spinning rotor was observed during the course of the experiments. A stainless-steel rotor was accidentally driven to a speed where considerable plastic flow took place. The pickup C_1 in traversing the spinning rotor radius showed a change in the contact potential of the surface where the plastic flow occurred. Since it was dangerous to repeat this experiment, the phenomenon was checked in a different way. A copper sheet was substituted for the stationary plate of the pickup C_2. The rotor was then spun at a convenient (250 rps) constant speed and the copper was stressed by pulling upward until plastic flow took place. The pressure around the rotor was 10^{-5} Torr. A small change in surface potential of the copper was observed during the plastic deformation. Similar effects were observed when aluminum strips were stressed. A careful examination of the two Duraluminum rotors used in the experiments failed to reveal any observable plastic flow so that it seems improbable that changes in contact potential due to plastic flow could have accounted for the potential changes observed.

In conclusion, the above experiments show that a small radial electrical potential gradient exists just outside of the surface of a spinning metal rotor. The apparatus developed for these measurements was also employed to investigate several phenomena which might influence the magnitude of this potential gradient. It was found that the interpretation of the experimental data was complicated by a number of factors arising from the residual gas surrounding the rotor, absorbed gases and oxide layers on the rotor surface, and possible distortions of the rotor surface. The experiments have shown that it is possible to evaluate accurately the emf's produced by magnetic fields even when the rotors are ferromagnetic. Consequently, it is now feasible to employ magnetically suspended rotors which together with the vacuum chamber can be out-gassed. Also, the gas pressure surrounding the rotor can be reduced to 10^{-10} Torr.[12] With this experimental arrangement it should be possible to make a clear-cut theoretical interpretation of the measurements. It is hoped that this more difficult experiment can soon be undertaken.

The writer is greatly indebted to Dr. J. W. Mitchell, Dr. D. Kuhlmann-Wilsdorf, and Dr. M. V. Barnhill, III, for most helpful discussions of the interpretation of the experimental results. Also, he is especially grateful to Mr. F. W. Linke, who constructed the centrifuge and assisted with the experiment.

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*Work supported by Army Office of Research, Durham.

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