AN ELECTROMAGNETIC METHOD OF DETECTING MINUTE IRREGULARITIES IN CURVATURE OF SPHERES AND CYLINDERS AND OF CON- TROLLING THE OSCILLATIONS OF A MASS OF METAL SUSPENDED BY MEANS OF A TORSION FIBRE

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It is well known that a single unidirectional alternating magnetic field is equivalent to two constant fields revolving with equal angular velocities in opposite directions and it is commonly believed

FIG. 1

that a coil of wire or a mass of metal placed in a uniform alternating field so that it can rotate will remain at rest if it happens to be at rest. The reason for this is that the two oppositely revolving fields which may be considered equivalent to the single impressed alternating field, induce two¹ symmetrical polyphase systems of currents of the

same frequency and amplitude. Therefore, the mechanical reactions between these currents and their corresponding fields are equal and opposite and the body experiences no resultant torque. If the body be given a start in either direction the opposite torques will no longer balance. For, suppose the body be given an angular velocity ω , and the angular velocities of the fields are p , and $-p$ respectively, then relative to the body one of the fields

¹ Steinmetz: A. C. Phenomena, 4th Ed., pp. 639-642.

will revolve with angular velocity $p-\omega$ and the other with angular velocity $p+\omega$. The two systems of induced currents now have frequencies proportional to $p-\omega$ and $p+\omega$ respectively and have different amplitudes. Therefore the mechanical reactions between the currents and the fields inducing them will no longer be equal and opposite. This is in essence the theory of the single-phase induction motor and explains why such a motor is not self-starting.

However, the writer has recently found in the course of an experiment with a copper ball suspended by means of a torsion fibre perpendicular to a uniform alternating magnetic field, that the ball will start to rotate even if it be perfectly stationary when the field is thrown on. It seemed to act like a self-starting induction motor, and inasmuch as according to well established electrodynamic theory such a motor cannot be self-starting, it became a matter of importance from theoretical as well as practical considerations to explain the existence of the extra torque. It was apparent that the starting torque was not an effect of the free electromagnetic oscillations produced by the sudden application of the field, for, as long as steady conditions in the field were maintained, the ball continued to oscillate about a definite new zero position. On repeating the experiment with both solid and hollow spheres and cylinders of different non-magnetic materials, it was found that the extra torque varied directly as the intensity of the "skin effect" for the different samples. Owing to the fact that all the spheres and cylinders had highly uniform curvature, it seemed difficult to attribute the effect to irregularities in curvature. Nevertheless this was assumed as a working hypothesis and two identical hollow circular cylinders were suspended alternately in the field. The observed deflections from the normal zero position were nearly equal for the two samples. When one of the samples was compressed so as to have an approximately elliptic cross-section, with the long axis about twice as long as the short one it gave a deflection many times larger than before distortion. Furthermore, the torque was always in such a direction as to tend to bring the long axis into coincidence with that of the field. A bronze ball-bearing was then suspended in the field and no starting torque was detected.

On linking together the two facts, first, that the torque on the asymmetric body increased with the "skin effect" and, second, that the torque always tended to make the body set its long axis in the direction of the uniform field the writer came to the conclusion that his discovery was only a new illustration of a fact already established but not generally known, namely:—

A conductor placed in a variable magnetic field tends to behave like a diamagnetic substance both in the way it disturbs the field and in the way it tends to move under the influence of that field.² The reason for this is that as the frequency of the impressed field rises the induced currents and magnetic fields tend to become concentrated in a thin layer near the surface and consequently the space within the body is traversed by a weaker field than before the introduction of the conductor. The higher the frequency the weaker will be the internal field. Indeed even in the case of iron the penetration of the field and currents may be so small at high frequency that the total flux through the space occupied by the body may be less than what it would be, were the iron removed. Dr. Louis Cohen³ has proved that in an iron cylinder of one centimeter radius subjected to an alternating magnetizing force having a frequency of a million cycles per second the total flux through the iron is only seven-tenths as much as the flux through that space before the introduction of the iron. It should also be remembered that whenever any body of a given permeability is immersed in a medium of a different permeability it will tend to move toward the region of lowest potential.⁴ For this reason a diamagnetic substance in a uniform magnetic field tends to turn its longest dimension in the direction of the field in contradiction to the statement frequently made that a diamagnetic substance turns its longest dimension across the field.

This diamagnetic behavior of a conductor in an alternating field has two practical applications. First, it affords a very sensitive method of detecting irregularities in curvature in metal spheres and cylinders and secondly, may serve as a means of

² J. J. Thomson: *Recent Researches in Electricity & Magnetism*, pp. 556-7.

³ *Calculation of Alternating Current Problems*, p. 38.

⁴ Poynting & Thomson: *Electricity & Magnetism*, pp. 257-259.

starting, stopping, and of controlling the oscillations of a mass of metal in experiments involving torsional oscillations of such a

FIG. 2

mass. In both of these applications a pair of Helmholtz coils will be found convenient for the production of a uniform field. The ball should be suspended midway between the coils. The mean distance between the centers of the latter should be about equal to the radius of the coils. If it be desired to test the ball for irregularities in curvature suspend it like a galvanometer coil with a small mirror attached to the suspension fibre for the purpose of observing the deflections of the ball. Before applying the field let the ball come to perfect rest and note the position on a scale of the reflected beam of light.

Throw on a field of ordinary frequency and determine the new zero about which the oscillations occur. The sensitivity of the method depends upon the magnitude of the "skin effect" for different materials and hence varies directly as the square root of the frequency of the impressed field and inversely as the square root of the resistivity of the material. In this case as with galvanometers the sensitivity depends also upon the stiffness of the suspension fibre and upon the distance of the scale from the mirror. Since the torque on the ball depends upon the reaction between the impressed field and the currents induced by that field, it will vary directly as the square of the amplitude of the field.

The writer had a mass of pure copper cast into the shape of a ball about two inches in diameter. It was then turned down and polished to be as nearly spherical as possible. Measurements with a vernier caliper showed deviations of any single diameter measurement from the mean, of about one-half of one per cent. On suspending the ball in a field alternating with a frequency of sixty cycles per second and having an effective intensity of about thirty gauss the torque due to the diamagnetic behavior of the

ball gave a deflection of several centimeters on a scale about a meter from the mirror on the suspension.

The second practical application of the diamagnetic behavior of a conductor in an alternating field is to the control of the oscillations of a torsion pendulum. There are some electrodynamic experiments and others of a purely mechanical nature based on the use of the torsion pendulum and require that the motion shall be purely torsional. For example, from the decrement of the oscillations of a mass of metal vibrating as a torsion pendulum in a constant field, it is easy to compute the resistivity of the material. Or one may wish to determine the coefficients of viscosity and of rigidity of a substance in the form of a fibre by the method of the torsion pendulum. In such experiments, mechanical methods of starting the oscillations are quite apt to produce a variety of undesirable modes of vibration. Moreover, in order to avoid troubles due to tremors of the building, it is often necessary to mount the apparatus in places not readily accessible. The magnetic control of the oscillations makes it possible to start the motion and to establish any amplitude by the mere closing of a switch. The only extra apparatus required is a pair of field coils, the metal being placed midway between them. The increase or decrease in amplitude is produced by closing the switch when the motion is either in the same direction as the torque due to the field or in the opposite direction.

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