

THE MEASUREMENT OF MAGNETIC PERMEABILITY.

BY ARTHUR WHITMORE SMITH.

IT is well known that when a ring of iron is magnetized by a current in a surrounding solenoid the iron does not instantly reach its full magnetization, but after the first large increase the magnetization continues to increase, in some cases, for several seconds. Ewing¹ observed this "viscous lagging" which "occurs in the softest iron and near the beginning of the steep part of the magnetization curve." Again he states² that this effect is more marked in soft iron than in hard iron, that it depends on the size of the sample tested, and that the cause is obscure. He also gives curves³ showing the effect of increasing the magnetizing force by small steps. At each step there was an immediate increase of magnetization, followed by a slow increase to the final value.

Lord Rayleigh⁴ tried to balance the effect on a magnetometer needle due to the magnetization of a bar of iron against the effect due to the current in a coil. A steady balance was impossible. "Most of the anomalous action was over in 3 or 4 seconds—the final magnetic state was not attained until after 15 or 20 seconds."

Wilson⁵ has noticed a large creeping up in the magnetic flux, even after one second. He states that the "effect is peculiar to the iron itself" and "might be influenced by induced currents." He computes (erroneously, I think) that the eddy current effect had entirely subsided in 0.9 second. More recently Jouaust⁶ has shown that the step-by-step method may give results as much as 12 per cent. in error, and he gives the warning that the sample tested should not be too thick. Rucker⁷ has found considerable difference between measurements by the ring ballistic method and magnetometer measurements. Using electrolytic iron Taylor⁸ has shown that owing to "magnetic viscosity" the step-by-

¹ Phil. Trans., Vol. 176, p. 569, 1885.

² Ewing, Magnetic Induction in Iron.

³ Proc. Roy. Soc., Vol. 46, p. 269, 1889.

⁴ Phil. Mag., Vol. 23, p. 230, 1887.

⁵ Proc. Roy. Soc., Vol. 62, p. 375, 1897-8.

⁶ Comp. Rend., Vol. 139, p. 272, 1904.

⁷ Zeit. für Instrumentenkunde, Vol. 25, p. 354, 1905.

⁸ PHYS. REV., Vol. 23, p. 95, 1906.

step method gives values for the magnetic induction considerably lower than those obtained by the method of reversals.

The question naturally arises, how much of the changing flux is measured by the ballistic galvanometer in the usual magnetic measurements? Such a galvanometer, having a period of about 16 seconds, will have completed its first throw in 4 seconds, and certainly cannot measure any change occurring after that time. At the very least, doubt is cast upon measurements made with this instrument under such conditions. The present paper shows that even the method of reversals with an ordinary ballistic galvanometer gives results which are too low, and the amount of this discrepancy for a ring of Swedish iron is shown in Fig. 2.

Some time ago there came into my hands a ballistic galvanometer having one remarkable characteristic. It is of the D'Arsonval type, period 40 seconds, and about as sensitive as other high-grade ballistic galvanometers, the remarkable property being that it is critically damped on a circuit of 70,000 ohms. When used on a circuit of a few ohms it is so greatly overdamped that it can move but slowly, and when once deflected it requires about 13 minutes to drift half way back to its zero position. It will therefore stand practically at rest at any point where it may be left, although it has a perfectly definite zero to which it will return in time. The action of this galvanometer is particularly interesting when it is connected to a few turns of wire around a bar magnet. When the magnet is slowly withdrawn, the spot of light on the galvanometer scale also moves slowly. If the magnet stops, so does the spot of light. When the motion is resumed the spot of light follows, and if the magnet be suddenly returned to its original position the spot of light returns as quickly and stops as suddenly. Every movement of the magnet is reproduced as faithfully as though the mirror were carried on the magnet itself. Of course, if the galvanometer is kept deflected too long there is the slow drifting back towards zero that was mentioned above, but if the movement is stopped with the galvanometer near its natural resting point it will remain stationary indefinitely. Perhaps the action of this galvanometer is best explained by saying that for every maxwell of flux cut by the wire around the magnet the coil of the galvanometer must move enough to cut one maxwell in the opposite sense. The instrument is, then, a fluxmeter rather than a galvanometer.

With the ordinary ballistic galvanometer the sudden reversal of the flux to be measured gives an impulse to the moving coil, and the scale is read at the end of the first throw. In using the new galvanometer the magnetic flux to be measured is reversed as usual, giving a quick deflection, at the end of which is a slow increase combined with the

return drift towards zero. After it has drifted back for half a minute or longer and has reached some definite line on the scale, the magnetic flux is reversed again, deflecting the galvanometer back to zero or a few spaces beyond. The slow increase is noticeable but the drift is negligible because the galvanometer is so near its resting point. After allowing about half a minute for the flux to reach its final value the scale is read, and this return throw is called the "deflection."

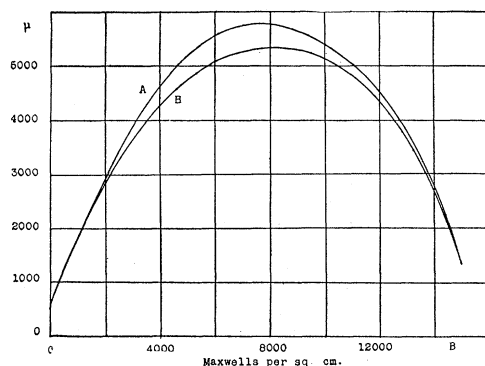


Fig. 1.

Permeability of Swedish iron. A. By new galvanometer. B. By ballistic galvanometer.

ured by each galvanometer, using first one and then the other. Both galvanometer scales were carefully calibrated over the range in which they were used, the readings for the calibration being interspersed with the other readings to avoid any error due to a change in the sensitiveness of the galvanometers.

At the highest magnetization each galvanometer showed the same values for the magnetic flux. At lower magnetizations the values of the flux as measured by the new galvanometer were considerably larger than the values given by the ordinary galvanometer. The values of the permeability computed from these two sets of measurements are shown by the curves A and B, Fig. 1. The higher curve is doubtless correct, and the lower curve shows that much is missed by the old type of gal-

In order to compare this new galvanometer with a D'Arsonval ballistic galvanometer of the usual type, both instruments were used to measure the same flux. A ring of Swedish iron was magnetized beyond saturation and the magnetizing current then reduced by small steps, it being slowly reversed 10 or 12 times at each step. At each point the flux through the ring was measured

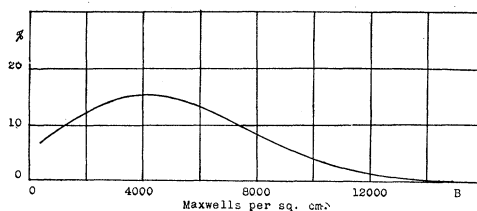


Fig. 2.

Percentage of magnetic flux not measured by the ballistic galvanometer (for a given value of H). For a ring of Swedish iron, 2 sq. cm. in cross section.

vanometer. The same thing is shown in a different way in Fig. 2, where the amount of flux not measured by the ballistic galvanometer is plotted as a percentage of the whole flux, and it is seen to be over 15 per cent. for values of B about 4,000 maxwells per square centimeter.

The measurements were repeated at different times and the same values were obtained at each trial. The amount missed by the ballistic galvanometer is approximately equal to that measured by the galvanometer when its key is closed later than the reversal of the current by a period equal to the time required for the first swing of the galvanometer.

There are two principal reasons why the magnetization lags thus behind the reversal of the magnetizing current. In the first place the primary current does not reach its full value instantly owing to the large self-inductance of the circuit with its many turns around the iron ring. When there is little other resistance in the circuit, and a battery of low E.M.F. is used, this slow rise of the current can be easily observed with an ordinary ammeter. "The time needed to establish a current of given strength in the coil of a large electromagnet with a solid core may be several minutes."¹

But in the results shown by the curves above the current was furnished by a storage battery of 35 volts and rose to its full value in a small fraction of one second. However, it was very evident that a considerable part of the magnetization was late, and occurred after the current had reached its steady value.

In the case of solid pieces of iron it is certain that there will be some current induced in the mass of the iron itself. This current will be greatest when the magnetization is increasing the fastest, and it will circulate in a direction opposite to that of the primary current. The effect of this eddy current (while it lasts) is, then, to reduce the resultant magnetic field which is impressed upon the iron, and of course the magnetic flux cannot increase faster than the impressed field.

To obtain more information regarding the cause of this slow magnetization a thin ring was cut from the side of the ring used above. All of the measurements were repeated with this smaller ring, which had one eighth the cross section of the former ring, but now both galvanometers gave the same results. The permeability curve is shown at A , Fig. 3. Only one curve is shown as the width of the line is sufficient to cover both curves obtained by the two galvanometers. This result was expected, but it was not expected that the permeability of the small ring should drop to half that of the piece from which it was cut. It was therefore unwound and heated to a dull red and allowed to cool slowly.

¹ B. O. Peirce, *Am. Acad. Arts and Sci.*, Vol. 43, 1907, p. 116.

After this annealing it was again tested in the same manner as before and the results are shown by curve *B*. As before the width of the line covers the two curves obtained by the two galvanometers. The permeability has nearly been restored and doubtless would be larger if

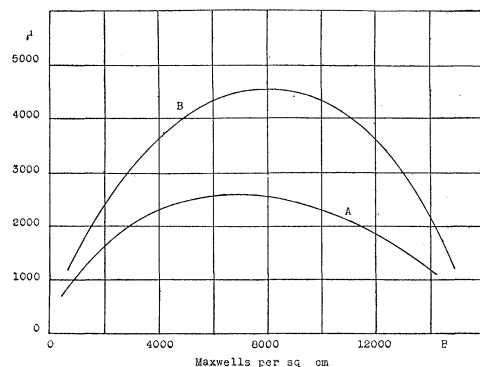


Fig. 3.

Permeability of Swedish iron. Points by both galvanometers are covered by the width of the lines. *A*. Thin ring cut from larger one. *B*. Same ring after annealing.

greater care had been taken in the annealing. There was some creeping of the magnetization, but the galvanometer key had to be closed one fifth of a second after the reversal of the current to detect as much creeping as was found after four seconds with the larger ring. It therefore seems reasonable to suppose that the slow increase of the magnetization is due to eddy currents in the iron of the ring, these currents tending to shield the interior portions of the iron from the changes in the field

impressed by the current in the surrounding solenoid. This agrees with the usual comment that the amount of the creeping depends upon the size of the sample studied and is absent in fine wires.

It is also interesting to see what very marked changes are produced in the permeability by the mere cutting of the iron in the lathe, an effect which must be present more or less in every sample that is thus prepared.

It follows from this comparison of galvanometers that the ordinary ballistic galvanometer does not give the correct measurement of magnetic flux even when the sample tested is only two or three square centimeters in cross section, especially if the permeability of the iron is high. In this case it is necessary to use an instrument which will respond quickly to changes of magnetic flux in order that the observations may not be too tedious, but which at the same time will have a period considerably longer than the time required for the iron to reach complete magnetization.

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