# AN OBJECTIVE REPRESENTATION OF THE HYSTERESIS OF IRON AND STEEL.[1]

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THE very happy thought of using cathode rays for the study of alternating currents and of alternating magnetic fields appears to have had its origin with Mr. Braun.[2] The method employed is obvious from Fig. 1, which shows a tube of the kind furnished by Geissler in Bonn, according to Braun's specifications. Cathode rays from the terminal *K* pass through a small hole in the diaphragm *D*, and produce a brilliant spot of light upon that portion of the screen *S* upon which they fall. This screen, which is covered with phosphorescent material, fills the end of the tube. The ap-

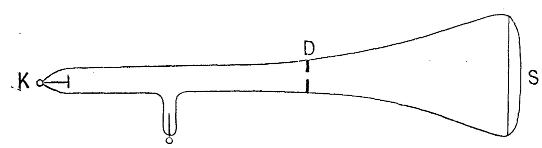


Fig. 1.

proach of a magnetic pole at *D* deflects the spot of light. If a small magnetizing coil, through which alternating currents flow, be fastened beneath the diaphragm, the spot of light is thrown into a vibratory motion which is capable of analysis by means of the revolving mirror. If two coils, placed perpendicular to each other, with their axes at right angles to the axis of the tube are fastened in the neighborhood of the diaphragm, and each of these coils be supplied with alternating current, the spot of light under the influence of the two forces is given a combined motion analagous to Lissajous's curves.

[1] Translated from the transactions of the Royal Academy of Sciences, Stockholm, 1899, No. 4, by E. L. N.

[2] Braun. Wiedemann's Annalen, 60, p. 552, 1897; Elektrotechnische Zeitschrift 19, p. 204, 1898. The latter article is known to me only through an abstract in Wiedemann's *Beiblätter*, 22, p. 884, 1898.

Braun, in addition to his other experiments, has investigated the velocity of the transmission of magnetization in iron. Since these experiments bear a certain relation to some of those which follow, I take the liberty of describing them in a translation of his own words.[1]

"An iron rod, 2 m. long and 9 mm. in diameter, lies in a horizontal position, perpendicular to the axis of the tube, its end as near as possible to the diaphragm. Along this rod, a small magnetizing coil may be moved. A second coil precisely similar to this, is arranged in a vertical plane, likewise perpendicular to the tube, so that under the simultaneous action of an alternating current in the two spools, the spot of light describes a curve, the form of which is determined by the pole lying nearest to the diaphragm. Both coils are traversed by the same alternating current.

"If the coil is moved along the rod, the shape and position of the ellipse of vibration changes and when the middle of the spool is about 42 cm. from the end of the rod a difference of phase of $\frac{\pi}{2}$ shows itself which is independent of the strength of the current. From the number of oscillations (50) of the alternating current it follows that the velocity of 'propagation' of magnetic excitation is eighty-six $\left(\frac{\text{meters}}{\text{seconds}}\right)$, a value which accords very well with that found by Oberbeck under similar conditions (88.7 meters for a rod 8.7 mm. in thickness, with a vibration frequency of 133)."

As Braun himself remarks, we have to do here with complicated phenomena, and it is a question whether the value of the velocity of transmission thus determined is really that of the magnetic excitation.

While engaged in repeating some of Braun's experiments, I asked myself whether it would not be possible by means of his apparatus to represent objectively the hysteresis curves in iron and steel and to exhibit the same, and after several preliminary attempts I found a simple arrangement which led, in a most beautiful manner, to the result. If a piece of iron or steel is magnetized in a magnetic field, for example in a long magnetizing coil, and if we plot a curve with rectangular coördinates in which the strength of the field $H$ is taken as abscissa and the induced magnetism $I$ as ordinate, we obtain, as

[1] Wiedemann's Annalen, 60, p. 557.

is well known (when $H$ passes through values from $H_1$ to $-H_1$), a curve which we call the hysteresis curve, and which owes its existence to the fact that induced magnetism in iron does not possess the same value when increasing and when decreasing for equal values of $H$. This curve and the surface enclosed by the same, which represents a certain amount of energy consumed in the cycle of magnetization, may be determined in a variety of ways and when changes in the magnetizing force take place slowly the process is one which offers no great difficulties. The relations are, however, much more complicated when the intensity of the field changes rapidly.

In the latter case losses of energy occur, as is well known, not only in consequence of the actual phenomena of hysteresis, but also in consequence of the action of Foucault currents. These which are generated in part by the inducing current in the mass of the iron, and in part by the induced magnetism itself, cause a retardation of the magnetic action upon the deeper layers of the substance (electro-magnetic screening). Attempts to separate these various factors from one another and to study them in detail have been made in recent times, among others by Ch. Maurain,[1] and by Wien.[2]

From their work one can form a clear conception of the difficulties with which such investigations are surrounded, and of the advantage of finding a simple method which would allow this relationship to be easily determined, which would make it possible to gain a ready acquaintanceship with the subject, and which, in other ways, would furnish a certain check upon the results. This has been attempted by Ewing,[3] who has constructed an apparatus that records the curves of magnetization automatically. In this apparatus a wire, which is placed between the poles of a permanent magnet, is traversed by a magnetizing current. Another wire carries a constant current and the latter is subjected to the action of the induced magnetism in the iron. The forces that act upon these wires turn a little mirror about two axes situated at right angles one to another. When the iron passes through a complete cycle of magnetization, a beam of light reflected from the mirror records upon a photographic plate

[1] Maurain; Annales de Chimie et de Physique; Series 6, 14, p. 208 (1898).
[2] Wien; Wiedemann's Annalen; 66, p. 859 (1898).
[3] Ewing; The Electrician; May, 1893.

the curve of magnetization. These and similar methods can, in the nature of the case, only be used where the changes in the magnetizing force take place slowly, since, as is the case with all mechanical devices, the inertia of the many parts introduces disturbances whenever the period of vibration is rapid.

*First arrangement of my apparatus.*—The first arrangement which I used will be easily seen from Fig. 2. The four coils, $S$, $S_1$, $M$, $M_1$, are fastened around the diaphragm in the manner shown. The dimensions of the coils are as follows:

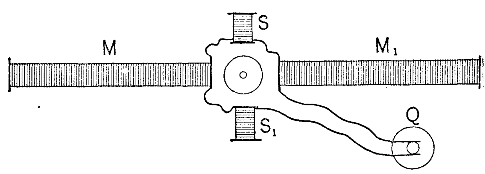

Fig. 2.

$S$, length 2 cm., external diameter 1.6 cm., internal diameter 0.5 cm., diameter of wire 0.3 mm.

$M$, length 20.5 cm., number of turns, 30 per second.

The coils, $S$ and $S_1$ were wound upon wood, $M$ and $M_1$ upon glass tubes. The current from a source $Q$ passes through these four coils in series. It flows through $S$ and $S_1$ (the indicator coils of Braun), in such a manner that the magnetic action of the same at the opening of the diaphragm is additive; through $M$ and $M_1$ in such directions that their action at the point is annulled. The horizontal deflection produced by means of the action of the current in $S$ and $S_1$ is proportional to the strength of the current and also to the magnetizing force. If a rod of iron be introduced into one of the magnetizing coils, the spot of light will be deflected in a vertical direction with a force which is proportional to the induced magnetism, so that under these circumstances the spot of light must pass through a true hysteresis curve.

*Second arrangement.*—The two indicator coils $S$ and $S_1$ retain their places, but they are slightly displaced backwards and forwards respectively, with reference to the plane of the diaphragm. The magnetizing coils $M$ and $M_1$ are placed parallel to each other and at equal distances from the diaphragm as shown in Fig. 3. The action of the current and of the magnetic field is the same as in the first arrangement. When currents of rather high intensity are used, it is easily possible to follow the movement of the spot of light directly with the eye. If, on the contrary, the cycle of magnetization is gone through with slowly, and especially if it is desired to measure the curve of hysteresis with precision, a photographic record is very advantageous. I set up the photographic camera in such a way that the images of the curves should be taken in half size. An exposure of from ten to twenty seconds suffices for the production of a good negative, which when developed and fixed, can be enlarged to any desired size by projection. The figures in the accompanying plate are reproduced directly from such negatives. The curves shown in the plate are from experiments upon hard steel wires 10 cm. in length and 0.175 cm. in diameter. I. was obtained from a wire containing 0.1 per cent.; II. from a wire containing 0.4 per cent. and III. from a wire containing 0.9 per cent. of carbon. I.–II., I.–III. and II.–III. are "difference curves" between these (I., II. and III.) taken two and two.

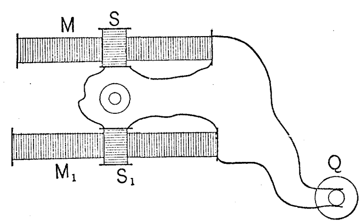


Fig. 3.

For very slow cycles, of magnetization (to produce static curves of hysteresis) I used as a source of current a storage battery, and varied the strength of the current by the introduction of liquid resistance, so as to change the magnetizing force between the desired limits. Alternating current was produced from a small hand-driven Siemen's alternating dynamo (from Ducretet in Paris) with which it was possible to vary the number of alternations between twenty and sixty per second. In this paper only a few examples of these experiments are given. I hope later to return to a more complete description of the results. Figs. 4–8 show drawings from some of the photographic records obtained with the second arrangement of the apparatus. The curves marked *A*, *B*, *C*, *D* refer to the following samples of iron :

(*A*) A rod of iron; length 10 cm., diameter 0.3 cm., amount of carbon 0.2%; tempered. (From Bofors in Sweden.)

(*B*) A rod of iron; length 10 cm., diameter 0.3 cm., amount of carbon 0.8%; hardened. (From Bofors in Sweden.)

(*C*) A bundle of very soft tempered iron wire, length 10 cm., diameter of each wire 0.082 cm.

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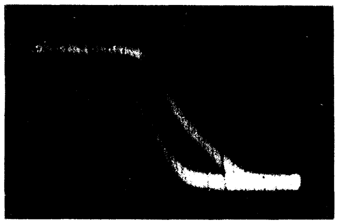

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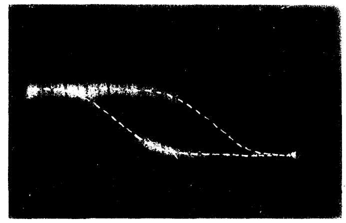

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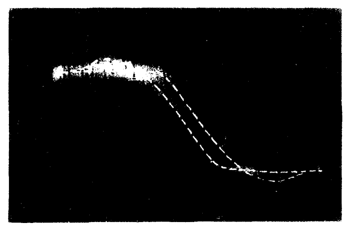

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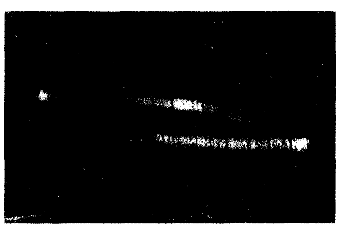

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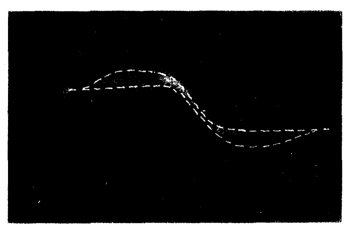

II–III

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(*D*) A precisely similar bundle of wires, surrounded by a tube of brass. External diameter of the tube 0.48 cm., internal diameter 0.30 cm.

Figure 4 shows the static curve of hysteresis. Figure 5 the corresponding curve for alternating current of about twenty reversals per second. Figure 6 shows the same curve for about sixty rever-

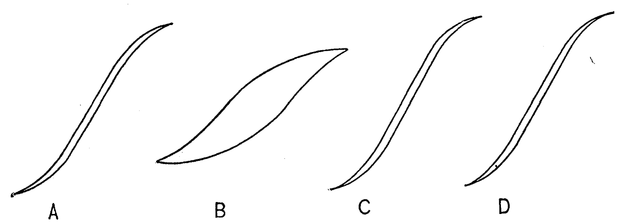



Fig. 4.

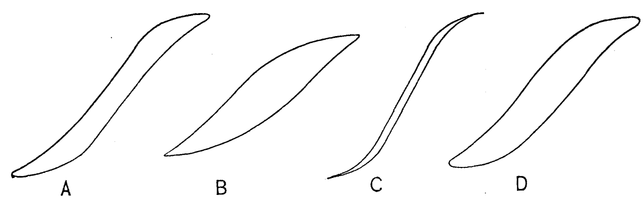



Fig. 5.

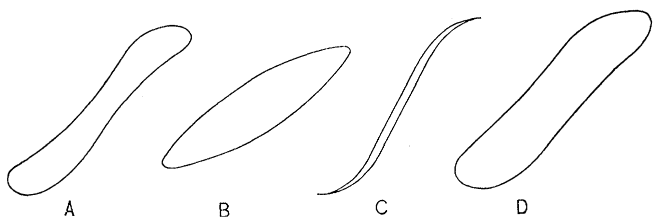



Fig. 6.

sals per second. The maximum strength of the current in these experiments was maintained as nearly as possible constant, with a value of two amperes. In the static hysteresis curves obtained by this method, the influence of hardness is easily recognized. In the case of very soft iron there is naturally no difference between a massive rod and a bundle of wires. In massive rods of soft iron with increasing frequency of alternations, the loops change greatly but in the case of hard iron, the change is insignificant. That these changes are almost exclusively due to the Foucault currents is evident from the experiments with the bundle of wires with and without the brass tube. The change in the loop with the number of alternations could not be detected in the case of the bundle, without the brass tube, in which case Foucault currents are almost completely excluded, but when the bundle was surrounded by the brass tube, the change in the loop was almost as great as in the case of a soft rod of massive iron.

In general, these results are in good agreement with the experiments of Maurain and of Wien in so far as they are capable of comparison with those investigations. Wien has used alternations up to a frequency of five hundred and twenty, and has studied the changes in the real hysteresis curves. Maurain finds that in the case of bundles of very fine wire, the loss of energy in the cycle of magnetization up to periods of fifty-five alternations per second is not appreciably dependent upon the frequency.[1] Unfortunately, I have not as yet had the means at my disposal to extend these investigations to a very high frequency.

A very interesting modification of the above mentioned experiment can be made by providing the magnetizing coils $M$ and $M_1$ with iron cores. The curves obtained in this way are difference curves, which depend upon the varied permeability and hysteresis of the specimens, as well as upon the strength and difference of phase which the Foucault currents in the same possess. Figures 7 and 8 afford examples of such difference curves for two different frequencies, obtained by the used of the two rods, $A$ and $B$, just described. In this case the difference curve for low frequencies is principally due to the difference in hysteresis. At higher frequencies, we have to do, in addition to the above, with unequal changes of phase of the Foucault currents. The curves in figure 8 were

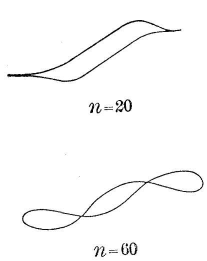


Fig. 7.

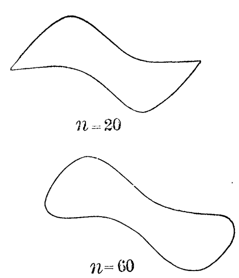


Fig. 8.

[1] Maurain, l. c., p. 279.

obtained by means of the bundles of wires, *C* and *D* (with and without the brass rod). In this instance, the hysteresis remains unchanged, and the difference curve is to be ascribed exclusively to the action of the Foucault currents. This last named arrangement of the experiment affords a simple and practical method of testing various samples of iron in respect to their magnetic properties, and likewise to the amount of carbon which they contain.[1] If we place in the magnetizing coils two precisely similar rods of iron of the same character, they neutralize each other and the spot of light moves in a horizontal straight path just as if no iron were placed in these coils. If the rods, however, possess different properties, we obtain more or less well marked difference curves. If, therefore, we have samples of iron, the properties of which are precisely known, we can compare with them directly the property of unknown samples of iron of the same dimensions. The usefulness of this application of the method in electro-technical work, and particularly in the construction of dynamo machines, where hysteresis is of great importance, is obvious.

If, in the first arrangement of the apparatus the rods of iron are brought with their ends very near the opening of the diaphragm and if the magnetizing coils in the second arrangement are fastened directly above and below the rods, and we compare the results obtained in these ways, with one another, it is found, particularly if the iron rods are of great length, that there is a very marked difference between the two curves. The hysteresis curves trend more slowly upward and downward in the first case than in the second. I was for a time at a loss to explain these facts, but I believe that the phenomenon is due to changes in the magnetic distribution within the rods with increasing magnetization. The following experiments confirm this opinion. If we make use only of the two long magnetizing coils, and arrange these as shown in Figure 9, we find when the diaphragm is at the point *a*, symmetrically located with reference to the two spools and when a bundle of iron wires is thrust into one of the tubes, that vertical vibrations take place. If now the diaphragm is pushed along to the point, *b*, *c*, etc., the di-

[1] This comparison is based upon the assumption that the iron in other respects is of similar chemical and physical structure.

rection of vibration tends to turn itself in such a manner as to be always perpendicular to the lines of the magnetic field. At the same time, we notice, however, that the line of vibration as is shown in Figure 9, becomes curved at the ends. If we replace the bundle of wires with an iron rod, we no longer get lines of vibration, but complete loops. With increasing intensity of magnetization, the system of lines of force is displaced, and the whole action is like a shifting of the poles towards the ends of the magnetized rod. If this shifting is not the same for increasing and diminishing magnetization, or in other words, it is connected with a hysteresis effect, we obtain the above described loops. Through this displacement of the poles, we may likewise explain the above difference in the curves obtained with the first and second arrangements of the apparatus.

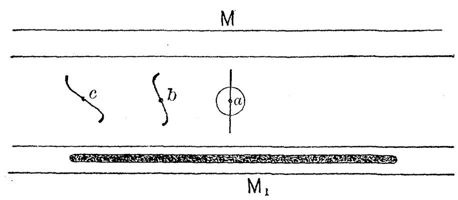
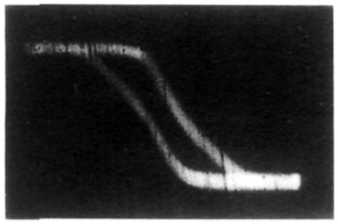


Fig. 9.

When short rods are used, and at a considerable distance from the diaphragm, the difference between the curves obtained is unimportant. The precise measurement of these curves would probably teach us much concerning the permeability and hysteresis of iron. Before entering upon this work in the case of certain varieties of Swedish iron, I purpose, however, to attempt important improvements in the cathode tube. I hope then to be able to work with currents of much higher frequency.

To Mr. Granqvist of the physical laboratory at Upsala, who assisted me in most of these experiments, I desire to express my heartiest thanks.



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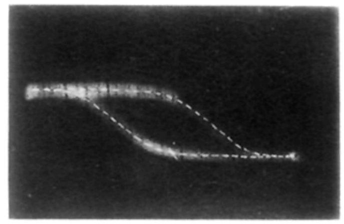

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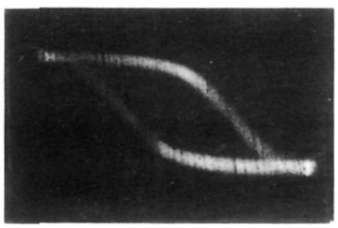

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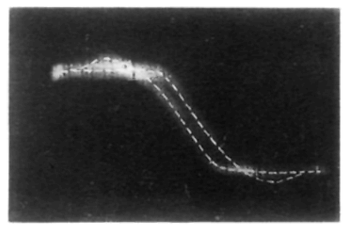

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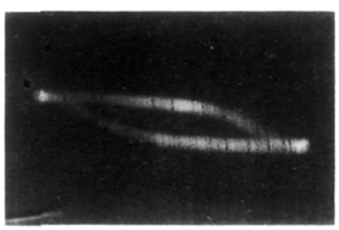

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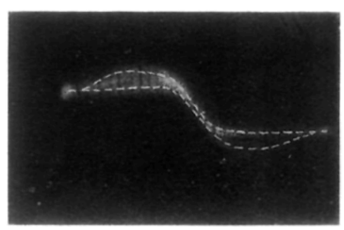

II–III

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