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LX. *On Electromagnets.*—No. I.

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To the Editors of the Philosophical Magazine and Journal.

GENTLEMEN,

THIS paper contains the results of the complete examination of two cylindrical electromagnets, with so much comment as is needed to show the nature of the generalization which is being worked out.

In the following tables of results, each normal place represents a number of experiments. The number of normal places has been reduced as far as possible consistently with exhibiting the course of the values.

The quantities are as follows:—

$\mathfrak{B}$, magnetic induction (number of lines of force through unit area, field intensity) through equatorial section of magnet ;

$$\rho, \text{ magnetic resistance} = \frac{\text{magnetic potential}}{\mathfrak{B}} \\ = \frac{4\pi nC}{\mathfrak{B}},$$

where n is the total number of coils, and C the current in C.G.S. ;

Earth's force, H, V ; $H = \cdot 1723$ in the mean,

$$V = \cdot 433;$$

ampere-turns $= 10 nC$;

f , focal distance in terms of length $= \frac{4\pi M}{l \times \text{lines of force}}$;

M , moment ;

$m, \frac{\text{moment}}{\text{volume}} = \text{magnetization.}$

The bars are wound uniformly from end to end. If the magnetizing coil be concentrated towards the middle the magnetic resistance is diminished.

The induction-coils are concentrated as close as possible to the equatorial section. If they are distributed more towards the ends, the apparent magnetic resistance is increased. Their number was varied between 200 and 1.

TABLE I.

Soft Iron Bar. .9379 centim. radius, 28.55 centim. long ;
957 windings.

$\mathfrak{B}$.	ρ .	Force, or ampere- turns.	f .	M.	m .
	centim.				
25.1	.343	Earth			
168	.315	42.0	.792	831	10.7
414	.272	89.5	.754	1,959	24.8
1,423	.237	268.5	.696	6,227	78.9
2,467	.238	467.6	.767	12,900	150.8
10,210	.233	1894	.754	48,400	613.3
17,214	.299	4099	.798	86,200	1093
17,858	.331	4704	.808	90,600	1148
19,289	.445	6832	.835	101,100	1281
19,650	.522	8159	.854	105,500	1337

The first entry is a mean between determinations made with the horizontal and vertical components of the Earth's force. The magnetic resistance of this bar under H (the less) was in every case less than that under V (the greater). This is opposed to the general run of the values. The mean eliminates this inconsistency, which is probably due in some way to residual magnetism.

TABLE II.

Soft Iron Bar. .4800 centim. radius, 30.00 centim. long ;
995 windings.

$\mathfrak{B}$.	ρ .	Force, or ampere- turns.	f .	M.	m .
	centim.				
28.2	.183	H			
73.5	.177	V			
541	.117	50.3	.726	679	31.3
1,207	.1058	101.7	.748	1,560	71.8
1,785	.0846	137.5	.704	2,173	100.0
5,675	.0850	384.0	.726	7,115	327.6
11,113	.0822	726.6	.718	13,800	635.4
14,093	.0836	938.0	.736	17,900	825.3
18,200	.134	1938	.793	24,900	1148
19,411	.180	2782	.814	27,300	1258
19,957	.263	4181	.869	30,600	1380
21,428	.385	6559	.885	32,800	1509

All calculations were made to 5 places, but only so many places are given as seem necessary in each case.

3. This was determined by the method given by Rowland (Phil. Mag. xvi. p. 140). The mean radius of the earth induction-coil is 25·65 centim. It has 21 turns, 3 layers of 7. The values of H and V employed were determined nearly every day. Latterly H alone was employed.

Earth's force.—The magnetic potential was taken as $H \times \text{length}$ or $V \times \text{length}$, as the case might be. The absolute values of H and V disappear from ρ .

Ampere-turns.—The currents were measured by two Helmholtz galvanometers, one having 18 coils and the other 2 coils; circumference 1 metre. The galvanometer-constant was kept in the form CH , so that the values of H obtained daily were conveniently employed.

Magnetic resistance.—The magnetic potential was thrown into the form $PH \tan \delta$. The induction also involved H . The quotient of these quantities was therefore independent of H . To secure identity of H in numerator and denominator, the tangent-galvanometer and earth induction-coil were always adjusted on the same standard place; being used alternately, the one could be removed to make way for the other.

Moment.—The moment was obtained by observing the deflection of a needle by the electromagnet placed at a known distance E or W . The scale and mode of computation employed in the absolute determinations were used. The value of H was always determined separately in the position of the deflected needle, by observing the deflection produced by the standard magnets, with which a complete determination had been made in the standard position the same day. The moment being known from the standard determination, H can be obtained from the deflection only.

These are all the observational data. With respect to f , I define the foci of a bar as being such that, if F be their distance, $F \times \text{lines of force} = 4\pi M$. This would be true if these points were true poles, and the points of application of the resultants of the lines of force. Then, to get a more general datum, I put $F/l = f$, so that the numbers from different bars may be directly comparable.

To study the values I take **3** for abscissa, conveniently so that 1000 is represented by 1 centim. Then any of the other columns may be represented by ordinates. ρ and f are the most important. In drawing the curves for ρ , I adopt a scale of 10 centim. for 1 centim. of ρ^* . It is easy to see how far the curves for f would assume the same general character.

* The woodcut is drawn to about half these dimensions.

As I propose shortly to undertake further experiments, I will only indicate the nature of the general conclusions.

Curves of Magnetic Resistance of Bars I. and II.

The magnetic resistance for each bar can be expressed as the sum of a resistance due to its form, and a quantity formed by dividing the length by μ , the permeability of the metal*. The form-resistance for different bars may be approximately represented by

$$\cdot 37 r 10^{-\cdot 0061 \frac{l}{r}}.$$

These constants are determined from the minimum resistances of the above bars, assuming that a further metal resistance, due to $\mu = 3000$, is to be subtracted from the values found.

The formula agrees with the values obtained from the bar and the 18 pieces (Phil. Mag. May 1883), when corrected for the erroneously assumed value of F (f in that paper). The error due to the value of H is not worth considering, as most of it appears in numerator and denominator. These errors all fall on the value of A in the formula

$$A r 10^{-k \frac{l}{r}}.$$

A would come to about $\cdot 36$ after correction. But k is unaffected by the errors, depending only on the ratio of the observed quantities. And taking as the result there that the ratio of the form-resistances of the bar and of one of the 18 pieces is $2 : 3$, we find at once $k = \cdot 006139$. The agreement of both constants is quite as close as can be expected.

As to f , it obviously follows a general course similar to ρ , except irregularities in the lower inductions, which I take to be connected with residual magnetism. But it can never

* The initial value of μ for I. would be about 240 (very near Rowland's value 232 for his magnetic ring), that for II. about 270. Both bars had been repeatedly magnetized to saturation.

approach very closely to 1. The values throughout the middle range, for both bars, are well represented by the formula

$$f = \cdot 650 + \cdot 440 \frac{\rho}{r}.$$

It is only for small inductions, and again for over 19,000, that this fails. It holds throughout the range of ordinary practice. In the following comparisons the last entry in each table is beyond the range for which it holds.

$$f = f_0 + C \frac{\rho}{r}.$$

$$f_0 = 64966, \log C = \bar{1} \cdot 64373.$$

Bar I. $r = \cdot 9379$.				
$\mathfrak{B}$	ρ .	f .		Calc. — Obs.
		Calc.	Obs.	
2,467	$\cdot 23784$	$\cdot 76161$	$\cdot 76734$	$-\cdot 00573$
10,210	$\cdot 23296$	$\cdot 75932$	$\cdot 75417$	$+\cdot 00515$
17,214	$\cdot 29928$	$\cdot 79046$	$\cdot 79787$	$-\cdot 00741$
17,858	$\cdot 33107$	$\cdot 80538$	$\cdot 80815$	$-\cdot 00277$
.....				
19,289	$\cdot 44536$	$\cdot 85908$	$\cdot 83466$	$+\cdot 02442$
Bar II. $r = \cdot 4800$.				
5,675	$\cdot 08504$	$\cdot 72796$	$\cdot 72626$	$+\cdot 00170$
11,113	$\cdot 08216$	$\cdot 72531$	$\cdot 71846$	$+\cdot 00685$
14,093	$\cdot 08363$	$\cdot 72666$	$\cdot 73590$	$-\cdot 00924$
18,200	$\cdot 13384$	$\cdot 77271$	$\cdot 79298^*$	$-\cdot 02027$
19,411	$\cdot 18011$	$\cdot 81515$	$\cdot 81437$	$+\cdot 00078$
.....				
19,927	$\cdot 26328$	$\cdot 89143$	$\cdot 86892$	$+\cdot 02251$

Generally, we may chiefly note that the course of the values does not at all indicate any definite limit to $\mathfrak{B}^\dagger$. The only limit that stopped me from forcing it up higher in both cases was that the coils became hot. In one case the coil of I. was actually charred.

It appears then, so far as the iron I am working with is concerned, that the existing idea of saturation is as complete a mistake as that of the existence of unalterable permanent magnets. And the idea of constructing measuring-instruments of an accurate character based on either principle is fallacious.

* There is evidently a discontinuity in this value.

† It is commonly assumed that $\mathfrak{B}$ cannot exceed about 17,500 or 18,000 (Rowland, *l. c.*; *Enc. Brit.* art. Magnetism).

The most accurate law to be drawn from these results is that, say, between $\mathfrak{B}=2000$ and $\mathfrak{B}=15,000$ the magnetic resistance does not vary more than about 2 or 3 per cent. for such bars as I have been using.

It must be remembered that $\mathfrak{B}$ here refers to the equatorial section of the magnet. Its average value throughout the magnet would be less.

My object has been to avoid refinements and deal with such conditions as obtain in practical work. Thus I have not touched the question of residual magnetism. I may note, however, with reference to a recent remark by Prof. Ewing*, that Rowland gave an account of the enormous values of residual magnetism in soft-iron rings in the paper before referred to; and the conditions of a wire or long bar approximate to those of a ring as far as the magnetic resistance is concerned. It is only when this is small that the residual magnetism is largely developed. I have a bar 1 metre long and 1 centim. in diameter, which retains a large charge just as Mr. Ewing describes.

Mr. Ewing remarks with surprise on the small magnetizing forces needed to produce large effects with his wires. I must point out that, if the bar be taken long enough, any difference of potential, however great, can be represented as a small magnetizing-force, since the force is potential / length. Further, this conception of magnetizing-force tacitly assumes that a long bar takes more potential to magnetize it than a short one. The reverse is actually true within practical limits. So that, by taking the bar long enough, the effect of a given difference of potential may be continually increased, and the corresponding *magnetizing-force*, as usually expressed, continually diminished up to a point beyond practical limits.

Synopsis of Formulæ.

$$\rho = \frac{l}{\mu} + \cdot 37r 10^{-\cdot 0061 \frac{r}{l}};$$

$$f = \cdot 650 + \cdot 440 \frac{\rho}{r}.$$

Then

$$\mathfrak{B} = \frac{4\pi \times \text{ampere-turns}}{10\rho},$$

$$M = \frac{f l r^2 \mathfrak{B}}{4}.$$

* Phil. Mag. November 1883, p. 382.