

Currents" (Proceedings, Royal Society, 17th January, 1889, vol. xlv.), investigates mathematically the screening produced by a conducting-plate, and shows that it is proportional to the thickness, and that if plates of different metals produce the same screening their thicknesses will be proportional to their specific resistances.

The screening mentioned by Professor Thomson is measured by the decrease of electro-motive force, while in these experiments the screening is measured by the decrease of magnetic force; and it is possible to have very considerable screening of electro-motive force and at the same time very little screening of magnetic force, for the magnetic field may be large though its rate of change is small. Professor Thomson (see paper mentioned above) found that a thickness of $\frac{1}{1700}$ of a centimetre of Dutch metal screened off all electro-motive force, and the thinnest films of metal he could obtain screened off all effect.

ART. XX.—*Magnetic Viscosity.*

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[*Read before the Philosophical Institute of Canterbury, 4th September, 1895.*]

THIS research was undertaken to see if steel or soft iron exhibited any appreciable magnetic viscosity when under the influence of very rapidly changing fields. Ewing had shown that there was a slow creeping-up of the magnetization for some seconds after the magnetizing force had been applied; but considerable difference of opinion has been expressed as to whether the area of the hysteresis curve would be less for a slow cycle than for a very rapid cycle of less than $\frac{1}{1000}$ of a second.

I had already designed the apparatus and the method of reducing the experiments before a copy of the Proceedings of the Royal Society, 20th April, 1893, reached New Zealand. I there found an account of experiments by Messrs. Hopkinson, Wilson, and Lydall, which in a great measure anticipated what I had intended doing. Later, when I received a copy of Gray's Absolute Measurements, I found an account of recent researches on the same subject (vol. ii., 753-758).

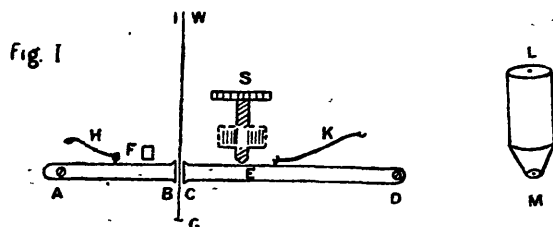
Messrs. Evershed and Vigneroles had shown that there was very little difference between the energy lost in magnetic

hysteresis at periods from 2 seconds to $\frac{1}{100}$ of a second. Hopkinson had obtained quite a marked difference between a slow and a rapid cycle, and had conclusively shown that the difference observed was not due to any time effect on the ballistic needle (Proc. Roy. Soc., 20th April, 1893). As the subject of the dissipation of energy due to magnetic hysteresis with varying periods is one of considerable interest, I determined to continue my experiments on the subject, especially as I was enabled to deal with intervals of time much shorter than those in Hopkinson's experiments.

In order to carry out these experiments a special form of apparatus for measuring short intervals of time was designed. It was necessary for the research to be able to measure the times of rise of currents in circuits whose self-induction was chiefly due to the amount of iron in the circuit. The "time-apparatus" was found to work very satisfactorily, and by its means time-intervals of less than $\frac{1}{100000}$ of a second could be with certainty determined.

DESCRIPTION OF THE TIME-APPARATUS.

A B, C D were two solid copper levers, pivoted at A and D respectively. The lever A B was kept pressed against a copper rod F by means of the spring H. The lever C D was kept pressed against the point E of a screw S by means



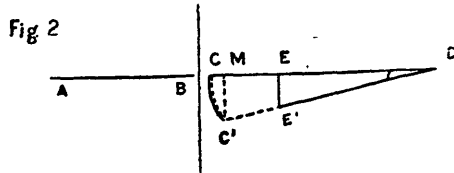
of the spring K. A vertical nickel wire W G, of length 6ft., passed between the extremities B, C of the levers, and was tightly stretched. A falling weight L M slid freely on this vertical wire. The shape of this weight is shown on the right-hand side of Fig. 1. A hole passed longitudinally through the falling weight, and, in order to prevent undue friction, the hole in the centre of the mass of metal was larger than at the ends, so that the wire could only touch the metal at the extremities L M.

In order to hold up the falling weight at any height on the vertical wire an electro-magnet was made to slide on the wire, and was held in position at any point by a screw. On turning off the current the weight fell instantly without communicating any movement to the wire.

When the ends of the levers B, C were exactly in the same horizontal plane the falling weight knocked the levers

from E and F simultaneously. If by means of the screw S the lever C D was depressed below A B, the falling weight reached the lever A B first, and after a certain definite interval the lever C D.

The interval of time was calculated as follows :—



Let A B, C D be the two levers when horizontal. Let the screw be given n turns, so that the lever C D is then in the position C' D. Let E and E' be the ends of the screw in the two positions. Let θ be the angle C D C'. Let h = height of weight above the first lever. The velocity with which the weight reaches the lever A B is given by $\sqrt{2gh}$, assuming the body falls freely under the influence of gravity. As the distance between the levers was never greater than $\frac{1}{2}$ in., and h was generally 3ft., we may assume the velocity to be sensibly constant over the interval.

Let d = distance between threads of screw :

$$\text{Then } E E' = nd.$$

Let C D = l ; E D = l_1 ; let C' M be vertical distance between the two levers :

$$\begin{aligned} C' M &= C' D \sin. \theta \\ &= l \frac{nd}{\sqrt{l_1^2 + n^2 d^2}} \\ &= \frac{l}{l_1} \cdot nd \left\{ 1 - \frac{1}{2} \frac{n^2 d^2}{l_1^2} + \&c. \right\} \end{aligned}$$

Now, nd in these experiments was never more than $\frac{1}{2}$ in., and $l_1 = 4.81$ in. The value of the correction due to C moving over the arc of a circle may therefore be neglected.

The time taken to move over the vertical distance C' M, assuming velocity constant, is given by

$$t = \frac{ndl}{l_1 \sqrt{2gh}}$$

In the actual experiments

$$\begin{aligned} d &= \frac{1}{40} \text{ in.}; \\ l &= 6.125 \text{ in.}; \\ l_1 &= 4.81 \text{ in.}; \\ h &= 3 \text{ ft.}; \end{aligned}$$

$$\therefore t = n \times 0.000192 \text{ nearly.}$$

\therefore the time to cross over an interval corresponding to one turn of the screw is 0.000192 seconds. The screw-head was

divided up into twenty divisions, and the apparatus was quite delicate enough to show a difference for every division of the screw-head when determining the times of rise of currents of very short duration.

The apparatus could therefore readily measure intervals of time up to $\frac{1}{1000000}$ of a second.

Now, this gives the time-intervals as derived from theory. In practice the time-intervals corresponding to one turn must be slightly greater, due to the retardation of the falling weight. The causes of the retardation are—(1) friction of the wire against falling weight; (2) the work done in knocking away the *first* lever; (3) friction of air, &c. As the wire was well oiled and placed exactly vertical, cause (1) is very small; as the weight was very heavy compared with the lever A B, the correction for (2) cannot be very great; and (3) is quite insignificant.

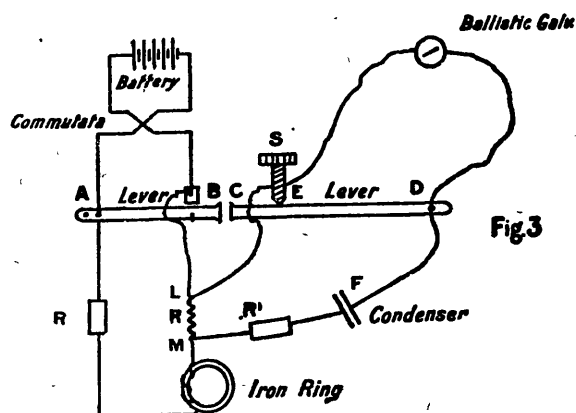
Later, experimental verification will be given that the calculated values are very nearly the same as the true values.

For the success of the experiments it was not necessary that the *absolute* values of the time-intervals should be known, but only that successive turns of the screw should correspond to equal intervals of time, and this, from the nature of the instrument, is very nearly true.

In order to determine the hysteresis curve for soft iron and steel when the current varied very rapidly, the time of rise of the magnetizing current for soft iron and steel rings was obtained by use of the time-apparatus.

ARRANGEMENT OF EXPERIMENT.

A battery of five Grove cells was connected to the binding-screws A and B of the time-apparatus. A wire led from B



through a non-inductive resistance r , thence round the iron ring which is to be experimented on, and back through a resistance-box R to the binding-screw A.

From one terminal L of the non-inductive resistance r a wire was taken to the back of the screw S. From the other terminal M a wire was led through a resistance-box R, and thence to one terminal of a $\frac{1}{3}$ microfarad condenser, the other terminal of which was connected to the binding-screw D in the lever of the time-apparatus.

A ballistic galvanometer was connected to S and D.

Since the levers AB, CD were of solid copper they acted as very low resistance shunts to the circuit RML and the ballistic galvanometer respectively. When the battery current is turned on only a very minute amount of the current passes round the circuit LMR, since its resistance is many thousand times greater than that of the lever AB.

We may therefore assume, for all practical purposes, that when the shunt AB is in position there is no current round the circuit LMR.

(1.) Suppose the two levers to be exactly level, so that the falling weight knocks them from their contacts simultaneously: When the shunt AB is removed the current commences to rise in the circuit AMB, the equation of rise being given by

$$CR = E - \frac{dN}{dt}$$

where C = current at any instant;

R = total resistance in the circuit;

E = total E.M.F. of battery;

N = total induction through the iron ring.

In all experiments the inductance of the connecting wires was very small, and can be neglected. The E.M.F. at the terminals of the non-inductive resistance r is given at any instant by

$$e = Cr.$$

Since the shunt ED is knocked from its contact E at the same instant as AB, the whole quantity of electricity required to charge up the condenser to the steady difference of potential between the terminals LM of the non-inductive resistance r flows through the ballistic galvanometer.

The throw of the galvanometer needle is therefore proportional to the maximum E.M.F. between the terminals L, M.

(2.) Now, suppose the lever CD is depressed by giving one turn to the screw:

On releasing the weight, the lever AB is knocked from B a certain definite interval before the lever CD is reached.

During the interval the current has been rising steadily in the circuit BMR.

The condenser is charged through the shunt ED, the E.M.F. e between its coatings at any instant being proportional to the current in BMR.

(The wires connecting the non-inductive resistance r to the condenser were short, so that we may assume, without any sensible error, that the difference of potential between the coatings of the condenser at any instant is equal to the E.M.F. between the terminals L and M of the resistance r .)

When the lever CD is reached, the remainder of the quantity of electricity required to charge up the condenser to the steady difference of potential passes through the galvanometer.

The throw of the galvanometer is therefore proportional to the value of $\frac{dN}{dt}$ at that instant.

By gradually increasing the distance between the levers by turning the screw we get a series of values corresponding to $\frac{dN}{dt}$ for different values of time.

When the current has fully risen $\frac{dN}{dt} = 0$, so that we then get no throw in the galvanometer, as the whole quantity flows through the shunt. Since the value of $\frac{dN}{dt}$ is known at any instant, the induction N through the iron for that instant may be calculated, and, since the corresponding current is known, we have all the data required to plot out the hysteresis curve for a very rapid cycle.

EXPERIMENTAL VERIFICATION.

In order to see to what degree of accuracy the time-apparatus could be depended on, the time of rise of the current in a coil of known self-inductance was compared with the theoretical time of rise as determined from the equation

$$C = \frac{E}{R} \left(1 - e^{-\frac{R}{L} \cdot t} \right)$$

The coefficient of self-induction L was very accurately determined. The mean value of L was found to be 2.315×10^7 cm. The period of the ballistic galvanometer needle in this and all succeeding experiments was 7 seconds. The sensitiveness of the shunt-levers of the time-apparatus was tested, and they were found to work perfectly, no correction having to be made.

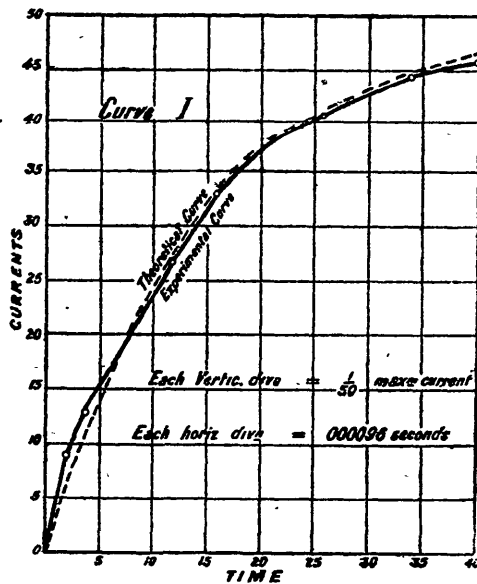
The resistance of the whole circuit was 15.65 ohms, and a battery of two Daniell's cells was used in this case.

The following are the results of a series of observations of the deflection of the galvanometer, and the number of turns of the screw at which the deflections were observed. Each observation is a mean of two experiments at least, and the curves in many cases were determined several times:—

Turns of Screw.	Throw of Galvanometer.
0	99½
1	82
2	74
3	65
4	58½
6	46½
8	34½
10	25
13	19½
17	12½
20	9½

The current has here only risen to nine-tenths of its maximum value. It was not convenient to have the levers separated by more than twenty turns, so that the whole curve is not completely determined. It has been shown that the throw of the galvanometer at any instant is proportional to $\frac{dN}{dt}$: i.e., to $L \frac{dc}{dt}$ in the case of a coil of constant inductance L .

A curve can therefore be constructed whose abscissæ represent time and ordinates current. The theoretical curve of rise, calculated from the equation $CR = E - L \frac{dc}{dt}$, is plotted alongside the experimental curve.



The close agreement between the two curves shows that the time-apparatus may be relied on to give very accurate

results. It also shows that the time-intervals theoretically calculated are the true intervals, and that successive turns of the screw correspond very accurately to equal intervals of time.

TABLE FOR CURVES 1.

(Dotted curve is the theoretical curve, and the other the experimental curve.)

Turns of Screw.	Observed Values.	Theoretical Values.
2	8.8	6.1
4	12.8	11.45
6	17.3	16.15
8	20.7	20.3
12	26.8	27.1
16	32.9	33.3
20	37.6	36.4
26	40.5	40.8
34	44.1	44.5
40	45.5	46.3

In the experiments on magnetic viscosity rings of soft iron and steel were taken, and the times of rise of the magnetizing current determined as explained previously.

Particulars of Soft-iron Ring.

Composed of iron wire 0.008in. in diameter, wound into a ring and thoroughly insulated from eddy currents by shellac varnish.

Mean diameter of ring, 8cm.

Sectional area of ring, 0.079 sq. cm.

Wound with three sets of coils of 511 turns altogether.

The magnetizing force corresponding to one ampère of current round the ring was 25.5 C.G.S. units.

Particulars of Steel Ring.

Composed of fine steel wire 0.01in. in diameter, insulated with shellac varnish.

Mean diameter, 8.3cm.

Sectional area of ring, 0.14 sq. cm.

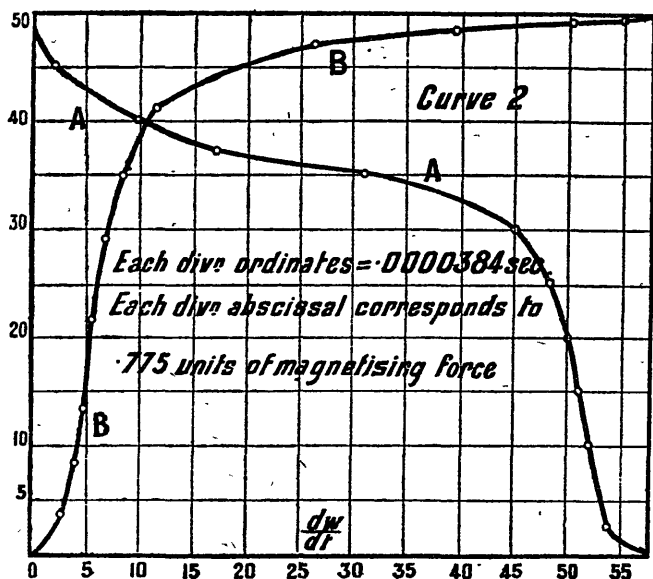
Wound with two sets of coils; total, 365 turns.

The static hysteresis curve for the soft iron and steel was very accurately determined. A special method was used, which allowed each individual point in the curve to be determined several times in succession.

From experiments with the time-apparatus it will be seen that the current rose to a maximum in the ring in about $\frac{1}{1000}$ of a second; so that the secondary current must have

all passed through the ballistic galvanometer long before there could have been any appreciable movement of the needle.

The hysteresis curve for the very rapid cycle was determined for the same maximum values of induction as the static curves, and under exactly the same conditions.



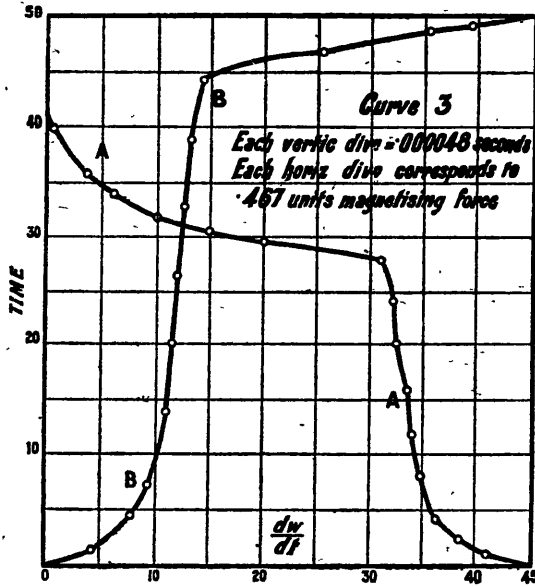
Curve 2 (A A) represents the relation between the values of $\frac{dN}{dt}$ and t (time) for the soft-iron ring.

Since $\frac{dN}{dt}$ * may be called the back E.M.F. in the circuit at any instant, when $t = 0$, $\frac{dN}{dt} = E$, the total E.M.F. of the battery. The value of the current flowing in the circuit at any instant is therefore known when $\frac{dN}{dt}$ is known. It will be observed that the value of $\frac{dN}{dt}$ changes rapidly at the beginning, and then very slowly when the steep part of the hysteresis curve is reached. The value of $\frac{dN}{dt}$ changes again very rapidly at the point where the hysteresis curve bends over, and gradually falls to zero as the iron reaches its saturation-value for the maximum magnetizing force.

Curve 2 (B B) is deduced from the curve A A. If we take any point in the curve A, the magnetizing force is known, and the value of the total induction through the iron corresponding

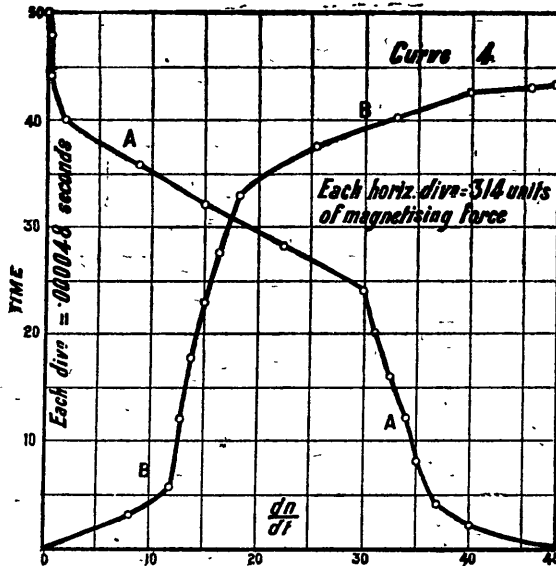
* In figures of curves erroneously printed as $\frac{dw}{dt}$ or $\frac{dn}{dt}$

to that magnetizing force is proportional to the area of the curve included between the axes, the curve A A, and the abscissa drawn through the point.



The values of B and H for any point may thus be determined.

The ordinates of the curve B B are drawn proportional to the induction, and the abscissæ to the magnetizing force.



From the curve, 2 (B B) curve 5 is plotted, showing the relation between B and H for the rapid cycle. The static ballistic curve is drawn alongside for comparison.

Curve 3 shows the corresponding relations for the steel-wire ring as curve 2 for the soft iron. Curve 6 shows the hysteresis curves for the slow and rapid cycles for soft steel. Curves 4 and 7 show the relations for a soft-iron ring when the maximum magnetizing forces is much lower than for the first two sets of curves. The value of H in this case was just sufficient to carry the magnetism of the iron up the steep part of the hysteresis curve.

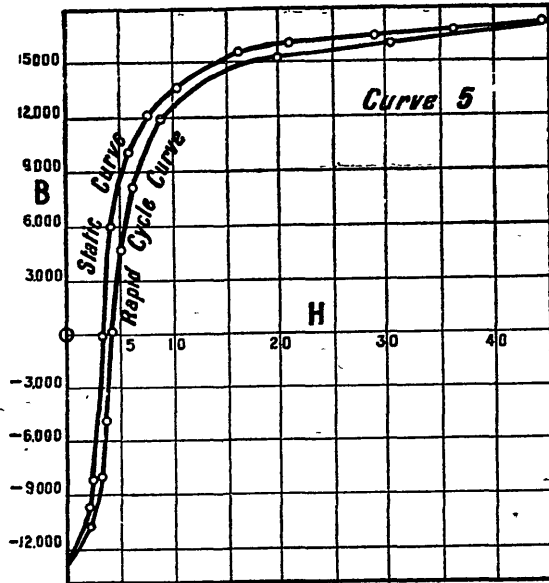


TABLE FOR CURVE 5.

Static Ballistic Curve.		Rapid-cycle Curve.	
Magnetizing Force = H.	Total Induction = B.	Magnetizing Force = H.	Total Induction = B.
0	- 12936	0	- 12936
2.35	- 9834	2.5	- 10709
2.75	- 8316	3.46	- 8060
3.76	- 264	3.85	- 4930
4.3	+ 5808	4.43	- 115
6.21	+ 10032	5.39	+ 4467
8.1	+ 12016	6.74	+ 8013
10.53	+ 13464	9.05	+ 11806
16.62	+ 15492	20.21	+ 15117
21.05	+ 15840	30.61	+ 16080
29.14	+ 16304	36.38	+ 16682
44.4	+ 17163	42.54	+ 17103
		43.7	+ 17132
		44.4	+ 17162

Several more curves for soft iron and steel, with different maximum magnetizing forces and different periods, were also obtained, but, as they showed the same effect as the curves 5, 6, 7, they are not given here.

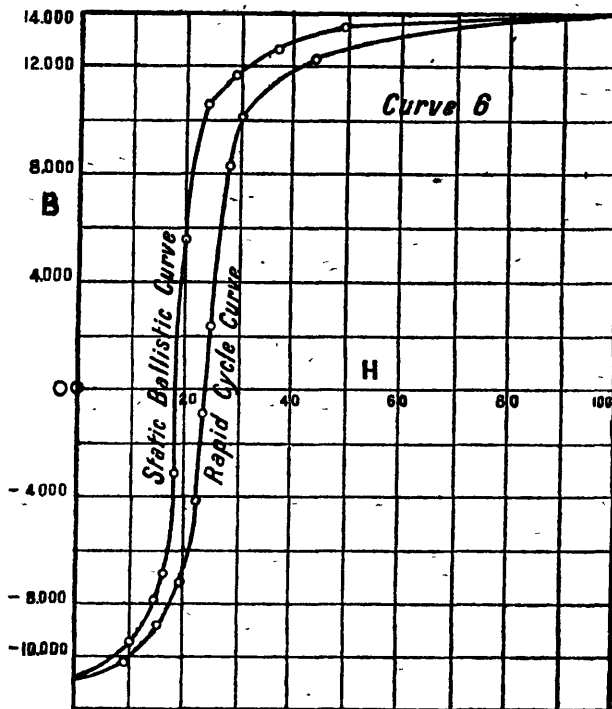


TABLE FOR CURVE 6.

Static Ballistic Curve.		Rapid-cycle Curve.	
Magnetizing Force = H.	Total Induction = B.	Magnetizing Force = H.	Total Induction = B.
0	- 11076	0	- 11076
7.8	- 10127	9.54	- 10326
10.63	- 9638	15.91	- 8826
12.45	- 8946	20.1	- 7474
14.94	- 7881	23.22	- 4076
16.6	- 6890	24.34	- 976
18.26	- 3817	25.4	+ 2174
20.75	+ 5603	27.52	+ 5274
24.07	+ 10543	28.5	+ 8374
29.05	+ 11608	30.73	+ 10224
36.52	+ 12567	54.1	+ 12374
48.8	+ 13019	64.7	+ 12724
96.3	+ 13952	75	+ 13174
		83.5	+ 13524
		88.5	+ 13774

The general results of these experiments conclusively show that soft iron and steel exhibit quite appreciable magnetic viscosity in rapidly-changing fields. The effect is far more marked in the case of steel than in soft iron.

The greatest departure of the slow-cycle from the rapid-cycle curve is shown at the "knee" of the magnetizing curve.

When finely-divided iron or steel is subjected to rapidly-alternating currents the loss of energy due to magnetic hysteresis is greater than for slow cycles. In the case of steel the loss of energy would be quite 10 per cent. more than for slow cycles, and in soft iron not so much.

In later experiments it was shown that the effect observed was in no way due to any screening of the interior mass of metal from induction. The iron wire of which the ring was composed was of too small diameter to exhibit any appreciable screening effect, due to induced currents, for the period investigated.

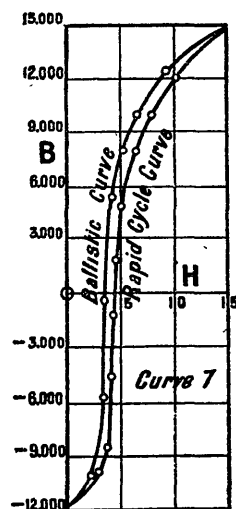


TABLE FOR CURVE 7.

Static Ballistic Curve.		Rapid-cycle Curve.	
Magnetizing Force = H.	Total Induction = B.	Magnetizing Force = H.	Total Induction = B.
0	- 11952	0	- 11952
2.1	- 9992	2.61	- 9845
3.21	- 5680	3.71	- 8546
3.68	- 692	4.01	- 4602
4.35	+ 5492	4.33	- 1204
5.29	+ 7844	4.65	+ 1794
6.7	+ 10045	5.2	+ 4805
9.25	+ 12548	6.7	+ 7810
14.44	+ 14704	8.08	+ 10186
		10.31	+ 12050
		14.44	+ 14704

In my paper published last year (Trans. N.Z. Inst., xxvii., art. lix.) it was shown that iron could be magnetized and demagnetized when the magnetism was reversed more than 100,000,000 times per second. Soft iron and steel exhibit the effect of magnetic viscosity quite strongly for a frequency of 1,000; but whether the loss of energy due to hysteresis increases

with the period is not yet known. The molecule of iron can swing completely round in less than a hundred-millionth part of a second; but it is quite probable that the magnetizing force required to produce any given induction is considerably greater for a frequency of 100,000,000 than for a frequency of 1,000. For very rapid frequencies the screening effects are so great that only a very thin skin of the iron is magnetized, and the effect of successive oscillations makes the interpretation of the results very difficult.

VARIOUS USES OF THE TIME-APPARATUS.

Not only was the time-apparatus a very simple means of determining the times of rise of currents in circuits when a steady E.M.F. was applied, but with different connections the duration of secondary induced currents at make and break of the primary could be examined under any conditions required. Very interesting information in regard to the screening effects of solid iron in rapidly-changing fields was deduced, and the subject of the gradual decay of magnetic force in magnetic and non-magnetic conductors, when the magnetizing force was removed, was experimentally verified. The behaviour of the magnetic metals when subjected to rapidly-changing fields is of great practical importance, and the need of very fine lamination of the iron for high rates of alternation is clearly shown in all the experiments.

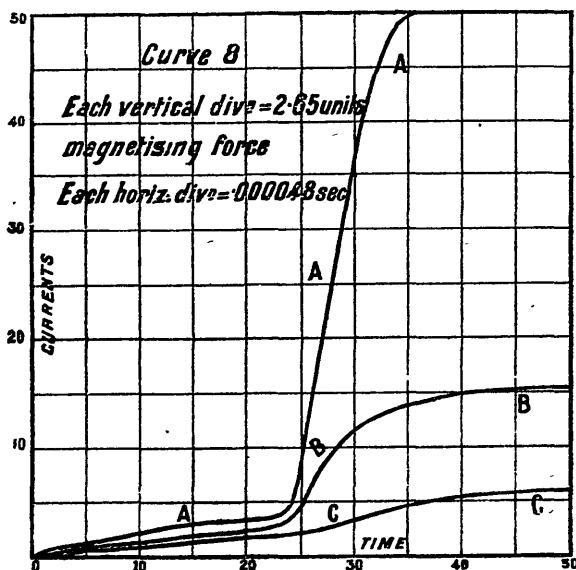
The principle of the time-apparatus can also be used to determine the velocity of projectiles at various points of their path. If two conductors, acting as shunts to the battery and galvanometer circuits respectively, be placed in the path of the projectile at a convenient distance apart, the time taken to traverse the distance between the two could be readily determined by observation of the amount of rise of the current during the interval. In a circuit of known inductance and resistance, the observed deflection of the galvanometer would be proportional to $e^{-\frac{R}{L}t}$; and, since $\frac{R}{L}$ is a constant for the circuit, t could readily be determined, and thus the velocity known. This method is purely electrical, and is capable of great accuracy. The determination of the constants of the circuit is a simple matter, and there are no sources of error introduced.

TIME OF RISE OF CURRENTS IN VARIOUS CIRCUITS.

In the experiments on magnetic viscosity the times of rise of currents in circuits containing iron were determined. It was observed that the nature of the curve of rise varied greatly

with the maximum current, and also depended on whether the iron in the circuit was solid or finely divided.

To illustrate the difference between the curves of rise for different maximum currents curve 8 is appended.



In curve 8 (A) the maximum magnetizing force is 132.6 C.G.S. units. After the steep part of the magnetizing curve is passed the current rises extremely rapidly, as is evident from the almost vertical line. Time of rise = 0.00173sec.

Curve 8 (B): Maximum magnetizing force, 38.7 units. None of the changes are so sudden as in the first curve. Time of rise = 0.00192sec.

Curve 8 (C): Magnetizing force, 15 units, which is just sufficient to ascend the steep part of the hysteresis curve. The current rises very gradually, and there are no sudden changes in the curve.

The times taken by the currents to rise in the three cases are nearly equal, notwithstanding the fact that the resistance in one case is nearly nine times that of the others.

In the above curves the iron was finely laminated, but when the iron is solid the current rises very rapidly for the first few ten-thousandths of a second, and then increases very slowly to its final value. This is due to the fact that only the surface-layers of the iron are magnetized at first, and the induction penetrates but slowly into the mass of the metal, due to the screening effect of induced currents.

With large solid electro-magnets the current takes in many cases over a second to rise to its maximum, and after

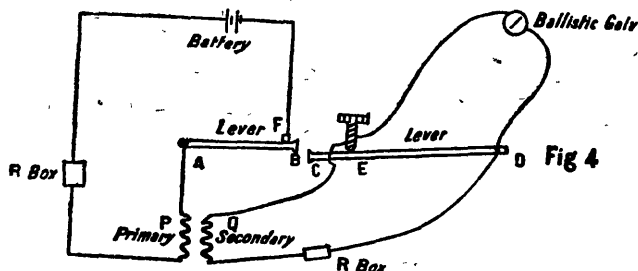
the first $\frac{1}{5000}$ of a second the curve of rise is nearly a straight line.

The curve of rise in the case of short cylindrical iron rods like the cores of induction-coils resembles very closely curve 1, for the inductance is sensibly constant.

If a closed secondary is wound over the primary the current rises much more rapidly than when the secondary is open, as we should expect from theory.

DURATION OF INDUCED CURRENTS AT MAKE AND BREAK.

The time-apparatus could not only be used for determination of times of rise of currents in various circuits, but also for determining the duration of the current in the secondary at make and break.



The method is a very simple one, and the duration of the secondary current may be determined under whatever conditions we please, since the resistance and inductance of the galvanometer does not affect the duration of the current in the circuit which is being experimented on.

One terminal of the battery is connected to F, and when the lever A B is in position the current passes along the lever B A, through the primary P, and through a resistance-box back to the other electrode of the battery.

The secondary circuit is connected through a resistance-box R and the shunt-lever C D. The ballistic galvanometer, is a shunt off the lever E D.

The resistance in the secondary Q E D R may be adjusted to any required value.

When the falling weight is released, on reaching the lever A B it breaks the primary. The induced current at break commences to circulate in the secondary round the circuit Q E D R.

No appreciable part of the current flows through the galvanometer, as the resistance of the lever C D is extremely low.

When the weight reaches the lever CD it breaks the secondary circuit Q E D R, and the *remainder* of the quantity of electricity induced at break flows through the ballistic galvanometer.

By varying the turns of the screw—*i.e.*, the interval between the break of the primary and secondary—the quantity of electricity which has passed through the secondary during the different intervals is easily determined.

It must be noted that the galvanometer does not influence the curve so obtained, as the deflection of the galvanometer is proportional to the quantity of electricity which has passed *before* the galvanometer is placed in the circuit.

The duration of the induced current in the secondary is dependent on the self-induction and resistance: the greater the resistance the shorter the duration, and the greater the inductance the more prolonged the duration.

Let L and N be the self-inductance of the primary and secondary circuits respectively, and M the coefficient of mutual induction; let R and S be resistances of primary and secondary; let x and y be the currents in primary and secondary: If E be the E M F of the battery, the equation of rise in the primary is given by

$$L \frac{dx}{dt} + M \frac{dy}{dt} + Rx = E;$$

and the equation of rise in the secondary

$$N \frac{dy}{dt} + M \frac{dx}{dt} + Sy = 0.$$

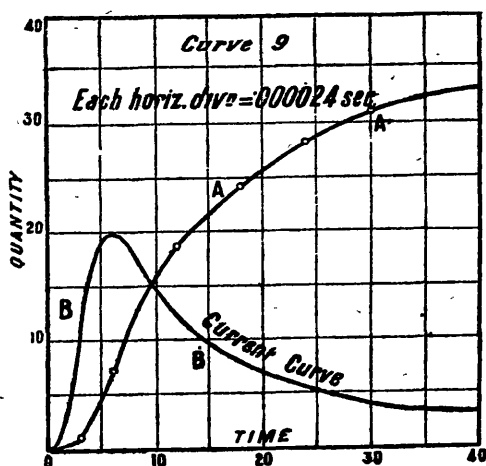
From these two equations x and y may be found when L, M, and N are constants. When iron, solid or finely divided, is in the circuit, the values of L, M, and N are variable, and the values of x and y cannot be determined.

The duration of the current in the secondary was determined under varying conditions of lamination of the iron, and a few of the more important results are given.

The duration of the induced current at break, when there was no iron in the circuit, was first examined. Two solenoids were wound over one another, and the secondary was of sufficient number of turns to give a convenient deflection in the ballistic galvanometer when the current was broken.

Curve 9 (A) shows the quantity of electricity that has passed in the secondary for different intervals of time.

Curve 9 (B) is the current-curve, and is deduced from 9 (A); for the current flowing in the circuit at any instant is given by $C = -\frac{dQ}{dt}$, where Q is the quantity of electricity that circulates in the secondary.

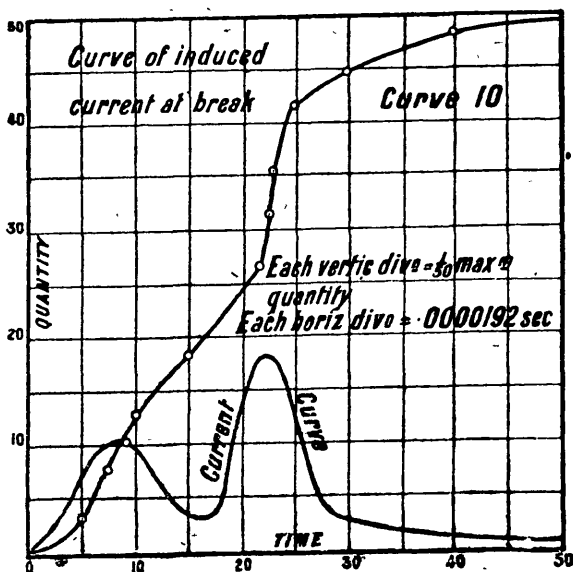


It will be observed that the current rises rapidly to a maximum, and then slowly decreases in value through a long interval of time.

When more than two-thirds of the quantity of electricity had already passed through the secondary, the slightest variation of the screw often caused large alterations in the deflection.

This irregularity in the deflections was evidently due to the fact that the current in the secondary was oscillating very rapidly.

It was not thought necessary to investigate the oscillations further, as the subject has been treated experimentally by Helmholtz, Schiller, and others.



Curve 10 shows what a marked difference there is in the current-curve in the secondary when iron is in the circuit.

A secondary was wound over the laminated core of a small induction-coil, and the duration of the secondary current determined. The current-curve exhibits two maxima, and is far more irregular than curve 9 (B). This was first thought to be due to some experimental error, but further investigations showed that the same peculiarity was exhibited by all the curves obtained. Curves were also obtained when finely-laminated iron and steel rings were used. The duration of the secondary could be varied by altering the resistance. When a large resistance was placed in the secondary the duration was very short. In the cases above considered the induced currents lasted about $\frac{1}{1000}$ of a second.

When solid iron is in the current the duration of the secondary is greatly prolonged, and is independent in a great measure of the *resistance* of the secondary.

A solid iron ring was taken and wound with appropriate magnetizing and ballistic coils. It was found that the secondary was of long duration. When 1,000 ohms were added to the current very little difference was observed.

If the lines of force had passed suddenly out of the primary, as in the case of the laminated core, the duration of the secondary induced current would have been diminished by increasing the resistance in the secondary; and yet in the case of the iron ring the effect was scarcely appreciable.

Clearly, then, the lines of force must pass out of the primary very slowly to account for the observed effect. The magnetic force in the iron changes very slowly when the current is broken, on account of the induced currents in the mass of the metal tending to prevent the decay of magnetic force through the iron.

DECAY OF MAGNETIC FORCE IN IRON AND COPPER CYLINDERS.

The very slow rate of decay of the magnetic force in an iron cylinder, which was observed in the experiments on the induced current at break, led to a series of more detailed experiments on the rate of decay of magnetic force when a uniform field was suddenly removed.

The subject is treated mathematically, p. 352–358, in Thomson's "Recent Researches," but I am not aware that the subject has been experimentally verified.

Suppose a metal cylinder be placed in a solenoid, and a steady current be sent round the solenoid. If the current is suddenly broken there are induced currents in the mass of the metal tending to maintain the original state of the magnetic field, and instead of sinking abruptly the field decays very slowly.

In order to experimentally test the rate of decay of induction in such a cylinder, a solenoid 10cm. long was wound uniformly with wire, ten turns to the centimetre. A secondary coil was wound over the primary, sufficient to give a convenient deflection in the galvanometer. On breaking the steady current flowing through the primary an induced current circulates through the secondary, and the duration of this secondary current depends on the resistance and inductance in the secondary circuit.

If sufficient non-inductive resistance be added in the secondary the duration of the induced current may be readily reduced to less than $\frac{1}{20000}$ of a second.

If the copper cylinder be now introduced into the solenoid the duration of the secondary is considerably prolonged, and its curve of rise and decay may be determined by the same method which has been used before.

The arrangement for the experiment is exactly the same as in fig. 4.

1,000 ohms non-inductive resistance was added in the secondary circuit, and the duration of the secondary was less than $\frac{1}{10000}$ of a second. The solid copper rod was now placed in the circuit, and at break the induced current was found to be considerably prolonged, due to the time taken for the magnetic force in the cylinder to decay.

From the fact that when there is no metal the whole current has passed in less than $\frac{1}{10000}$ of a second, we see that the current circulates in the secondary almost instantaneously after the lines of force pass out of the primary. When the copper cylinder is placed in the solenoid the quantity of electricity that flows in the secondary for any definite interval is proportional to the number of lines of force that have passed out of the primary in that interval.

Let N = total induction through secondary; let a and b be the areas of primary coil and copper cylinder respectively:

The induction through the copper = $\frac{b}{a} \cdot N$.

The part of the induction $N \left(1 - \frac{b}{a}\right)$ decays very suddenly; but the induction through the copper decays gradually.

On pages 356, 357, "Recent Researches," a table is given for the theoretical calculated values of the rate of decay for a series of values $\frac{t}{T}$ where

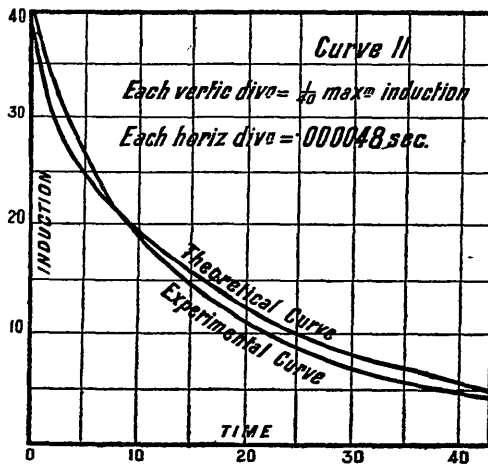
$$T = \frac{4\pi\mu r^2}{\sigma}, \text{ where } r \text{ is radius of the cylinder.}$$

Now, for this experiment, assuming $\mu = 1$, $\sigma = 1,600$,

$$T = 0.0069 \text{ sec. approximately :—}$$

Theoretical Table.

$\frac{t}{T}$				Total Induction.
0.00	..	..	..	1.0
0.02	...	...	...	0.7014
0.04	...	...	...	0.5904
0.06	...	...	...	0.5105
0.08	...	...	...	0.4470
0.10	...	...	...	0.3941
0.20	...	...	...	0.2178
0.30	...	...	...	0.1220
0.40	...	...	...	0.0684
0.50	...	...	...	0.0384



Copper Cylinder.

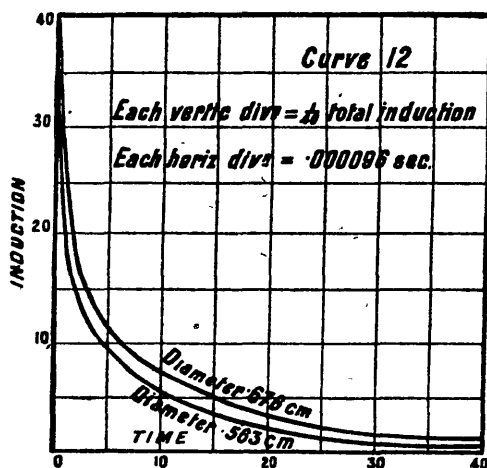
Curve 11 shows the rate of decay of the total induction through a copper cylinder 1.875cm. in diameter. The close agreement between the theoretical and experimental curves is a confirmation of the mathematical theory, for the difference between the two is quite within the limits of experimental error. The induction falls rapidly at first, and then very slowly, so that a long interval elapses before the induction has fully fallen.

In 0.00074sec. the induction has fallen to half its original value.

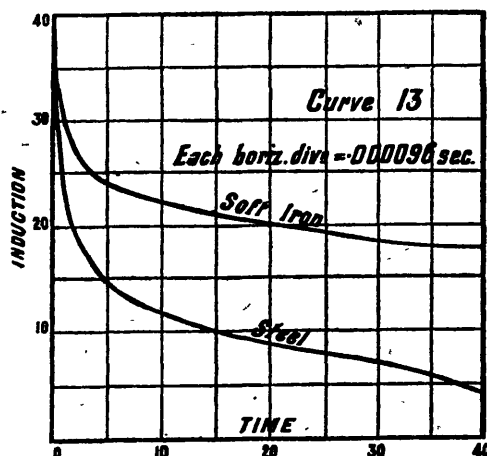
Soft-iron Cylinders.

Curve 12 shows the rate of decay of induction in soft-iron cylinders of diameter 0.676cm. and 0.573cm. respectively. The rate of decay is much slower than in the case of copper, on account of the high permeability of the iron, although the diameter and conductivity are less for the iron than the copper.

The greater the radius of the cylinder the longer the induction takes to decay.



In this case the induction falls extremely rapidly, and in about $\frac{1}{10000}$ of a second has fallen to half its original value. The subsidence of the remainder is much more gradual.



Soft-iron and Steel Rings.

Curve 13 shows the fall of induction for soft-iron and steel rings of sectional diameter 0.93cm. It will be observed that the rate of decay of the induction is much slower when the magnetic circuit is complete, as in the iron and steel rings, than in short cylinders of metal.

SUMMARY OF RESULTS.

1. For finely-laminated iron, the lines of force pass out into the secondary circuit very rapidly after the magnetizing current is broken. It was experimentally shown that the

iron did not take more than $\frac{1}{10000}$ of a second for the rearrangement of the molecules into their final position; so that there is no appreciable time-effect in the demagnetization of finely-laminated iron.

2. In solid iron cores the induction decays very slowly compared with non-magnetic metals.

3. In iron and steel the decay is very rapid at first, and then very gradual.

4. The rate of decay of induction is more rapid in a short cylinder of iron than in a ring of the same dimensions, and is more rapid for steel than for soft iron of the same diameter.

5. The decay of induction in iron is purely due to the reaction-effect of induced currents in the mass of the metal, and is in no way due to any true time-effect in molecular rearrangement.
