On Magnetic Lagging and Priming in Twisted Iron and Nickel Wires.

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In 1886, Professor Wiedemann published some very interesting experiments on the effects of twist on iron and nickel wires, variously magnetised.* These, however, were in themselves too few to guide us to any very clear knowledge of the relations of magnetism and twist. A consideration of them at once suggested innumerable lines of enquiry, and opened up vast gaps in our knowledge which prolonged experiments alone could fill. Shortly put, here is an iron or nickel wire of certain dimensions, magnetised in a certain manner either permanently or temporarily, and subjected to a particular straining involving twist. The problem is to find how all these different possible variable quantities or qualities depend on one another.

With a view to work out some small part of this huge problem, I sketched out a line of research, which was partly carried through in 1887 by Mr. K. Imagawa, a graduating student of Physics in the Imperial University of Japan. During the first six months of that year, many distinct series of experiments were made.

The complete discussion of these and other experiments carried

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* See Wiedemann's Annalen, Vol. XXVII., p. 377; translated in the Philosophical Magazine (1886).

out later forms a part of a series of papers on the relations of magnetism and twist which I am communicating to the Royal Society of Edinburgh. In the present note I wish to call special attention to one point, namely the character of the lag in magnetic change due to twisting. The peculiarity discovered by Mr. Imagawa was that, for a particular amount of cyclic twisting, the curve showing the corresponding changes in magnetic moment of the twisted wire, if regarded as an area gone round in the proper direction, changed its algebraic sign. This Mr. Imagawa established for iron and nickel wires, circularly magnetised by a current passing along them, and also for nickel wire longitudinally magnetised by a current passing in an enclosing helix of wire. Nearly all the experiments were made with circularly magnetised wires; and the few experiments with longitudinally magnetised nickel were made with the view of finding if the same curious reversal of magnetic lag was obtained with it. By a strange oversight Mr. Imagawa did not observe at the time that circularly magnetised iron wire showed the same peculiarity as nickel; consequently he did not search for an analogous effect in longitudinally magnetised iron. It was only when I came to collate the results of all his experiments that the reversal effect was found to exist also in the case of iron. By that time, however, the various effects of twist on longitudinally magnetised iron and nickel wires had been elaborately investigated by Mr. Nagaoka, whose paper follows immediately on this one. It is because of the obviously close connection between certain of Mr. Imagawa's observations of two years ago and Mr. Nagaoka's more recent results that I have thought it well to discuss the former in this place.

The particular class of problems proposed for investigation was this: Study the effects of different twists upon the magnetic properties of different wires, along which currents of various strengths are kept steadily flowing. Obviously the wire is, to begin with, circularly magnetised ; and, if it is isotropic as regards magnetic susceptibility, it should show no longitudinal polarity. It is almost impossible, however, to obtain a wire of magnetic metal free from such polarity. All the usual precautions were taken. The wires were roasted and allowed to cool as they lay perpendicular to the magnetic meridian ; and the wire which was being studied lay horizontally in the same direction: opposite the one end of the wire a magnetometer of the usual mirror device was set ; and the other end of the wire was fixed to the twisting apparatus. In order to avoid jars and jolts, the twist was not applied directly by the hand, but was effected by means of a gearing of toothed wheels. For every complete rotation of the handle worked by the hand, the axle which formed the continuation of the wire moved through a few degrees. At the same time the resistance of the gearing was considerable, so that it was an easy matter to keep the hand working at a fairly uniform speed. In this way the twisting of the wire was effected very gently and gradually.

We know already from Wiedemann's experiments that, when such a circularly magnetised wire is twisted right-handedly with reference to the current flowing along it, it becomes longitudinally magnetised, the magnetic intensity being co-directional with the current in the case of iron wire, but anti-directional in the case of nickel wire. After the wire has been twisted and untwisted repeatedly through a considerable range—4° per centimetre in Wiedemann's experiments—a corresponding cyclic variation is impressed upon the longitudinal intensity. From a large positive value at or near the one limit of twist, the magnetic intensity changes to a nearly equal negative value at or near the other limit of twist. The average apparent polarity of the wire, as indicated by the deflections of a magnetometer placed opposite one end, is approximately zero.

The most complete series of experiments made by Mr. Imagawa was with a nickel wire of diameter 0·49 millimetres and length 56·4 centimetres. A current of one-third of an Ampère was kept steadily flowing along it; and the wire was subjected to a succession of definite cyclic twistings, each cyclic twisting being continued until the corresponding magnetic changes went through a steady succession. Very complete cycles were taken for the following total to-and-fro twists of the wire as a whole, namely $\pm\frac{\pi}{2}$, $\pm\pi$, $\pm\frac{3\pi}{2}$, $\pm 2\pi$, $\pm 8\pi$. These correspond respectively to twists per centimetre of $\pm 1^{\circ}{\cdot}6$, $\pm 3^{\circ}{\cdot}2$, $\pm 4^{\circ}{\cdot}8$, $\pm 6^{\circ}{\cdot}4$, and $\pm 25^{\circ}.6$. The numbers are given in Table I., and are represented graphically in Plate XXV.

The first column on the left gives either in ordinary degrees or in multiples of π the successive stages of the twisting, beginning with the greatest negative twist. The second column gives, in approximately C. G. S. electromagnetic units, the corresponding longitudinal magnetic intensities of the twisted wire from the greatest negative twist to the greatest positive twist. The third column, which should be read from below upwards, gives the intensities as the wire is, so to speak, untwisted from the greatest positive twist to the greatest negative twist. The fourth column is obtained by subtracting the numbers in the third column from the corresponding numbers in the second. The algebraic sign of these differences shows the character of the magnetic lag. Any given algebraic sign applies to all numbers below it, until a number is reached which has the opposite sign.

Table I.

(Date of Experiment: April 18 & 19th, 1887)

TOTAL TWIST.	LONGITUDINAL INTENSITY.		MAGNETIC LAG.
− 90°	+ 74·4	+ 74.4	0
70	66·3	59·8	+ 6.5
50	55·8	42·5	13·3
30	38·4	21·4	17
10	17·4	− 2·5	19·9
+ 10	− 6·2	− 24·8	18·6
30	30·1	42·8	12·7
50	47·4	57·0	9·6
70	63·2	68·2	5
90	76·3	76·3	0
− 180	+ 142·3	+ 144·8	− 2·5
150	134·2	132·1	+ 2·1
120	120·3	116·9	3·4
90	101·1	95·8	5·3
60	71·6	72·9	− 1·3
30	35·7	37·2	1·5
0	− 6·5	− 1·9	4·6
+ 30	45·9	44·0	1·9
60	79·4	77·5	1·9
90	102·3	107·3	+ 5
120	120·9	123·4	2·5
150	137·6	137·3	− ·3
180	146	146	0
− 270	+ 194·4	+ 192·8	+ 1·6
225	183·5	184·1	− ·6
180	164·3	173·6	9·3
135	137·3	150·7	13·4
90	98	122·8	23·8
45	40	84·9	44·9
0	− 26·4	29·1	55·5
+ 45	81·5	− 37·8	43·7
90	119	97·3	21·7
135	154·1	138·3	15·8
180	171·4	162·8	8·6
225	187·2	178·9	+ 1·7
270	191·6	191·6	0

Table I. *(Continued.)*

TOTAL TWIST.	LONGITUDINAL INTENSITY.		MAGNETIC LAG.
− 360°	+ 210.8	+ 211·4	− ·6
270	191·0	206·2	15·2
180	138·6	187·2	48·6
90	41·5	153·8	112·3
0	− 73·8	88·0	161·8
+ 90	151·3	− 31·0	120·3
180	187·9	133·9	5·4
270	198·1	190·3	7·8
360	213·3	213·3	0
− 8 π	+ 244.6	+ 190·7	+ 51·9
7	213·9	192·8	21·1
6	144·2	191·3	− 47·1
5	53·9	190·0	136·1
4	− 12·7	186·6	199·3
3	65·7	182·9	248·6
2	111·6	174·5	286·1
1	147·3	163·7	311
0	172·1	147·6	319·7
+ 1	189·7	122·5	312·2
2	202·1	93	295.1
3	210·5	49·6	260·1
4	215·8	0·3	216·1
5	217	− 67	150
6	218·6	143·5	75.1
7	218·6	198·4	20·2
8	219·2	219·2	0

The curves corresponding to these numbers are shown in Plate XXV., Fig. A. The arrows at the ends of the curves indicate the directions in which they are to be gone round. Thus the curve for twist $\pm \frac{\pi}{2}$ is to be gone round clock-wise. In it, as shown by the algebraic sign of the numbers in the fourth column of Table I., there is true magnetic lag. That is, the magnetic change lags behind the strain which causes it. The curve is distinctly open. Passing to the twist $\pm\ \pi$, we see that the magnetic lag is sometimes positive, sometimes negative, but is in all cases very small. Hence the curve can hardly be called open, the going and returning branches being nearly coincident. On the whole, however, as we may see by adding the "lag" numbers, the lag is still positive. This twist may be regarded as being almost exactly the critical twist at which the magnetic lag changes sign ; for in the next curve, that for twist $\pm \frac{3\pi}{2}$, the "lag" numbers are nearly all negative and markedly so. In fact for this and for higher twists the phenomenon ceases to be one of lagging, but becomes really a case of what might be called magnetic "priming." That is, the magnetic change, as it were, runs ahead of the straining that causes it. In other words, the rate at which the longitudinal magnetic intensity, whether positive or negative, falls off during untwisting from either limit to zero is greater than the rate of growth during twisting. It will be noticed that the curves for the higher twists are of the same character as the one given by Wiedemann (*Annalen d. Phys. u. Chem.*, Bd. XXVII., Taf. III., Fig. 8.).

In Figure A, as given, the curve corresponding to the twist $\pm\ 8\,\pi$ is not shown to the same scale as the others. It is represented to the right as a dotted curve, with the scale of twist diminished to one-eight and the scale of intensity diminished to two-fifths. The greater openness of the curves for the higher twists, after the critical twist has been passed, is very striking. At the same time it is to be noticed that the range of intensity reaches a practical limit at a very moderate twist. These peculiarities are well shown in Table II. and in Figures B and C which illustrate it.

In Table II., the first column gives the different cyclic twists, the second column the total ranges of intensity, and the third column numbers proportional to the areas of the closed cyclic curves. These areas are easily calculated from the differences given in the fourth column of Table I, and are in fact the best indicators of the nature and magnitude of the magnetic lagging or priming.

Table II.

TWIST.	RANGE.	AREA ÷ π
$\pm\frac{\pi}{2}$	150·7	+ 11·5
$\pm\pi$	289·5	+ 1·8
$\pm\frac{3\pi}{2}$	385·2	− 58·9
$\pm 2\pi$	424·4	− 260·3
$\pm 8\pi$	437·2	− 2804·7

Curve B shows how the range depends on the twist. The increase is rapid and nearly steady for the small twists ; but for higher twists than $\pm 2\pi$, the rate of increase of range becomes very small. It should be mentioned that this point was very fully investigated by Mr. Imagawa ; and that the conclusion just stated does not rest merely on these five particular cases.

Curve C shows the march of the area of the cyclic curve with the twist. Thus the area begins positive at the low twists, indicating true magnetic lagging. For a twist a little greater than $\pm\pi$, the area changes sign, so that we have magnetic priming. For higher twists the area goes on increasing at a very rapid rate. So far as the experiments were carried there seems to be no limit to the increase of this area. An incomplete cycle for ± 20 π indicates an approximate area of 10,000 π. At these very high twists, the wire must of course be severely strained ; the great regularity of the magnetic effect is, in the circumstances, all the more remarkable.

With these results before us, a very natural enquiry was as to the existence of similar peculiarities in the case of longitudinally magnetised nickel wire. Mr. Imagawa had time only for a few experiments, but these were enough to establish the existence of the peculiarity. The most complete results of these experiments are given in Table III. The first column gives the twists in ordinary degrees or in multiples of π ; the second and third columns give, as in Table I, the going and returning measurements of the magnetic condition of the wire ; and the fourth column gives the differences between the corresponding numbers in the second and third columns. The numbers are not given in absolute measure, but simply in terms of the scale unit.* The wire used was 0·85 millimetres in diameter and 52 centimetres in length. Thus the twists as given correspond to twists per centimetre of ± 0°·58 , ± 0°·87 , ± 1°·16 , ± 1°·73 , ± 2°·32 , ± 3°·47 , ± 6°·94 , ± 17°·3.

The results are graphically shown in Plate II., the twists being taken as abscissae and the relative intensities as ordinates. All the curves are double-looped, and are nearly symmetrical for the higher cyclic twists. For the first five cycles, namely, ± 30° , ± 45° , ± 60° , ± 90° , ± 120° , there is true magnetic lag, the return curve at either limit always being above the other. In the curve for ± 180° , ± 2 π , and ± 5 π , however, the magnetic lag becomes negative. This change in algebraic sign is also shown by the signs of the numbers in column four of Table III, as will be at once seen

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* Mr. Imagawa has, indeed, left no record of the constants of the magnetising coil which he used, so that it is impossible to reduce the numbers to absolute measure. So far as the present discussion is concerned, this is, however, of no real importance.

Table III.

(Date of Experiment. May 31st, 1887).

Total Twist.	Longitudinal Intensity.		Magnetic Lag.
+ 30°	256·2	255·8	+ 0·4
20	256	255	+ 1·0
10	255·9	256·8	− ·9
0	257·2	258·4	− 1·2
− 10	258·4	261·6	− 3·2
20	260·9	264·2	− 3·3
30	265·7	265·7	0
+ 45	273·5	274·4	− 0·9
30	272·6	267·9	+ 4·7
15	271·5	268·8	+ 2·7
0	273·4	275·2	− 1·8
− 15	275·3	282·7	− 7·4
30	281·6	288·9	− 7·3
45	292·2	292·2	0
+ 60	290·1	288	+ 2·1
40	286·4	274·7	+ 11·7
20	280·8	272·4	+ 8·4
0	274·7	281	− 6·3
− 20	277·9	292·9	− 15
40	282·1	303·1	− 11
60	308·5	308·5	0
+ 90	316·1	317	− 0·9
60	309·9	300·9	+ 10
30	294.4	271	+ 23·4
0	272·6	278·2	− 5·6
− 30	278·7	305·1	− 26·4
60	306·4	322·6	− 16·2
90	329·9	329·9	0

Table III. *(Continued.)*

TOTAL TWIST.	LONGITUDINAL INTENSITY.		MAGNETIC LAG.
+ 120°	333·4	333·5	− 0·1
90	327·2	319·5	+ 7·7
60	312	296	+ 16
30	284·6	268	+ 16·6
0	259	259·6	− ·6
− 30	272	288·5	− 16·5
60	300·6	317·7	− 17·1
90	325	333·4	− 8·4
120	339·2	339·2	0
+ 180	339	338·1	+ 0·9
135	328	329·5	− 1·5
90	297	318	− 21
45	254·5	274·6	− 20·1
0	244·5	242·2	+ 2·3
− 45	278·8	251·5	+ 27·3
90	313	298·7	+ 14·3
135	332	329	+ 3
180	341·5	341·5	0
+ 360	345·6	344·3	+ 1·3
270	310·6	344·5	− 33·9
180	244·5	340	− 95·5
90	247·8	324	− 76·2
0	297·4	292	+ 5·4
− 90	331	248	+ 83
180	347	248·5	+ 98·5
270	352	315·5	+ 36·5
360	352	352	0
+ 5 π	340	344	− 4
3 π	247	346·5	− 99·5
π	334·5	344·7	− 10·2
− π	351	324·4	+ 26·6
3 π	349	240	+ 109
5 π	347·6	347·6	0

if the numbers for ± 120° and ± 180° are compared. Thus, somewhere between these two twists just named, there is a critical twist for which the wire would probably show no magnetic lag at all. It will be noticed how the curves open out as the twists are taken higher and higher. They open out much more rapidly than they appear to do in the Plate; since, for convenience of representation, the curve for ± 360° is plotted to half-scale as regards twist, and the curve for $\pm\ 5\pi$ (shown dotted in the diagram) to a quarter scale. Here also, as in the curves for the circularly magnetised wire, the range of variation of the magnetic intensity increases rapidly with the twist for small twists, but comes practically to a limit just about the critical twist for which the magnetic lag vanishes. In a series of similar experiments on permanently magnetised nickel wire, Mr. Iwagawa failed to obtain any indication of change of sign. The permanent magnetism rapidly diminished as the twistings were taken larger and larger; the range during twisting reached a distinct maximum for a twist of ± 90°, and then rapidly fell off, so that for a twist of ± 360° it was hardly measurable. But throughout, the magnetic lag was always positive.

I now pass to the results for iron. Some of these are given in Table IV. arranged exactly as were the numbers for nickel in Table I. It hardly seems necessary to give the curves. Enough to say that they are very smooth, very similar in general outline to the corresponding curves for nickel, but differ from these in being so to speak their inversion, such as would result from reflection in a plane mirror. The numbers in the fourth column are obtained by subtracting the second column from the first, so that for true lag the differences are positive. The wire used was 58 centimetres long and 0·64 millimetres in diameter. The current along the wire was 1·4 ampères. The intensities are given in approximately absolute electromagnetic units (C. G. S.)

Table IV.

(Date of Experiment. March 4-7, 1887.)

Total Twist.	Longitudinal Intensity.		Magnetic Lag.
− 90°	− 184	− 183	+ 1
60	180	135	45
30	170	51	119
0	149	+ 93	242
+ 30	92	151	243
60	+ 61	173	112
90	184	184	0
− 180	− 318	− 314	+ 4
120	315	262	53
60	306	141	165
0	258	+ 184	442
+ 60	16	295	311
120	+ 233	320	87
180	325	325	0
− 270	− 348	− 345	+ 3
180	352	309	43
90	340	193	147
0	270	+ 190	460
+ 90	+ 120	329	209
180	289	352	63
270	− 351	351	0
− 540	− 384	− 387	− 3
360	391	386	+ 5
180	307	362	− 55
0	+ 224	199	− 423
+ 180	359	+ 314	− 45
360	382	388	+ 6
540	383	383	0
− 720	− 392	− 384	+ 8
540	395	386	+ 9
360	391	382	+ 9
180	+ 215	373	− 588
0	363	332	− 695
+ 180	386	95	− 481
360	392	+ 311	− 81
540	392	394	+ 2
720	386	386	0

As in the case of nickel, so here, the magnetic lag is positive for the smaller and negative for the higher twists. The change of sign occurs, however, at much higher values of twist. In Table V. we see the relations between the twist, the range of intensity, and the area of the cyclic curve, clearly shown. Others are included than those given in Table IV.

Table V.

Twist.	Range.	Area ÷ π
± 45°	94	+ 14·9
± 90°	368	127
± 135°	530	247
± 180°	641	353
± 225°	666	387·5
± 270°	704	467
± 540°	779	− 513·5
± 720°	789	− 1821

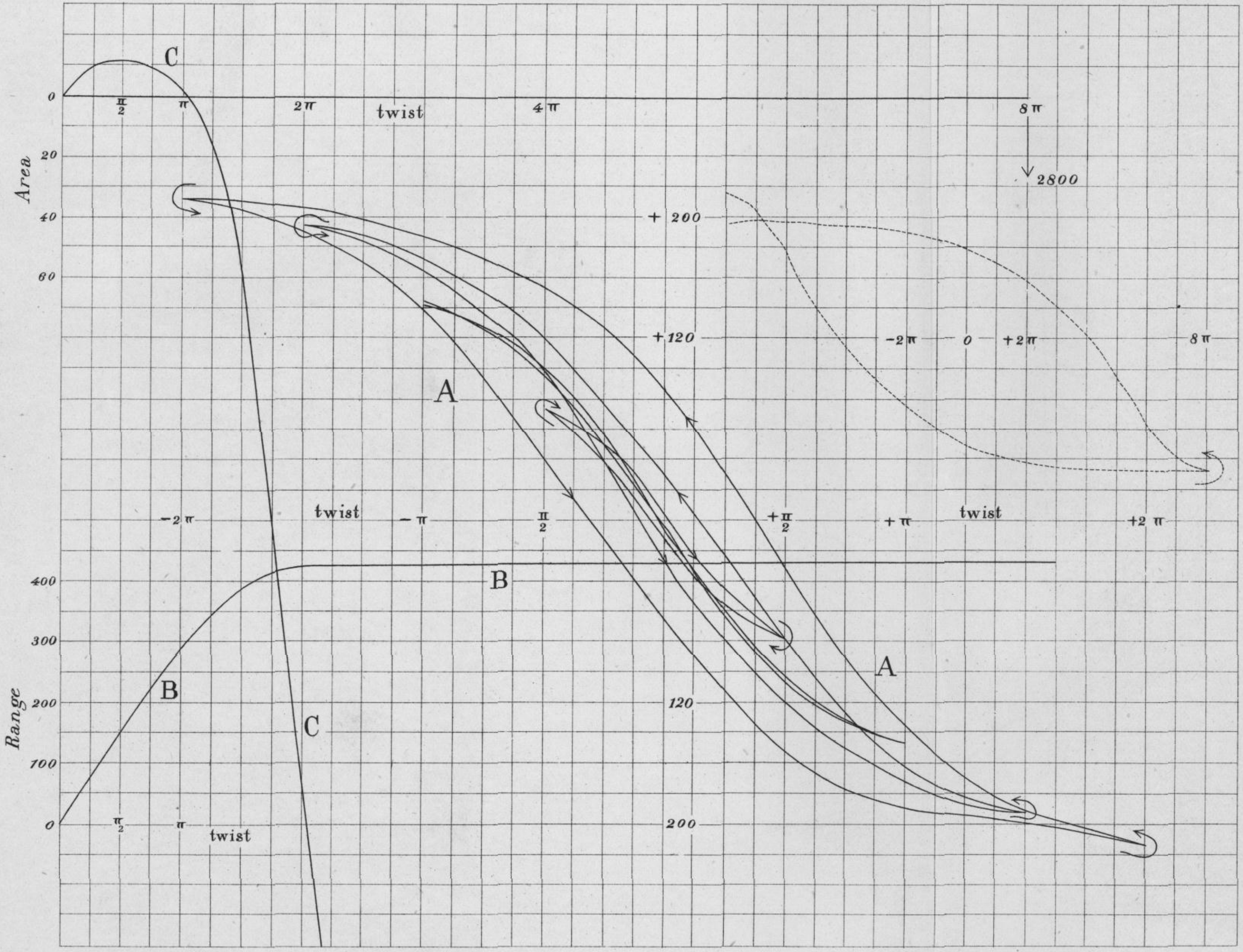
Thus, exactly as in the case of nickel, the range very soon approximates to its limiting value, while the area, once the critical twist is passed, seems to grow rapidly as the twist increases.

An interesting feature of the iron curves at the high twists is that the greatest and least intensities do not occur at the limiting twists. In other words, the curves have a distinct S shape with true maximum and minimum points. This feature appears first in the experiment for the twist ± 135°, for which the full numbers are not here given; but it does not become distinct and undoubted at both limits of twist until the twist of ± 270° is attained. Thereafter it is an invariable feature.

In seeking for an explanation of these phenomena of magnetic lag, we must bear in mind the essential difference between experiments in which the mechanical strain is the cause of magnetic change and those in which magnetising force is the cause. Take for example the well-known case, so frequently discussed, of a wire subjected to a continuously varying longitudinal field. Here in virtue of magnetic retentiveness, there is always true magnetic lag as the field is diminished from its highest value. The magnetic force is, in part, simply removed. But when the wire is twisted through a large angle, the effect of untwisting the wire is no mere *removal* of twist, but is really a *superposition* of an opposite twist. Now, we know that the induced magnetism due to a given field is apparently destroyed by a reversed field of smaller value. It is this effect, rather than the effect of mere diminution of the field to zero, that is to be compared to the effect of untwisting, especially if it is untwisting from a large twist. If the twist is small, however, that is, not greatly beyond the limits of torsional elasticity, the untwisting will be aided by the elasticity of the wire, so that it will have something of the character of a mere undoing. From this point of view, then, small twistings and untwistings will be to a certain extent comparable to applying and removing magnetising force; while large twistings and untwistings are to be compared rather to applying first a given magnetising force and then a small reversed magnetising force. Hence for small cyclic twistings, the magnetic lag is a true lagging effect; but for large cyclic twistings it becomes really a "priming" effect. The fact that the limits of torsional elasticity for iron are much greater than the same for nickel fits in admirably with the result established above that the critical twist at which the lag changes sign is much higher for iron than it is for nickel

There is, however, another and perhaps a simpler explanation of the phenomenon. It is suggested by some results of experiments of the same nature which I have carried out very recently. The experiments are not quite completed; but enough has been done to show that, in the case of nickel (and in certain circumstances, iron also) magnetised circularly by a current passing along it, the *positive* lag is eliminated if the wire is tapped or kept in a state of forced vibration. Thus it may be that the tendency of cyclic twisting is to produce negative magnetic lag; but that the effect is modified by the magnetic retentiveness of the undisturbed wire, a retentiveness which is generally explained in terms of molecular friction.

The two explanations suggested are not altogether rivals. It is quite possible indeed, that both may be true, being simply somewhat different ways of looking at the phenomena involved.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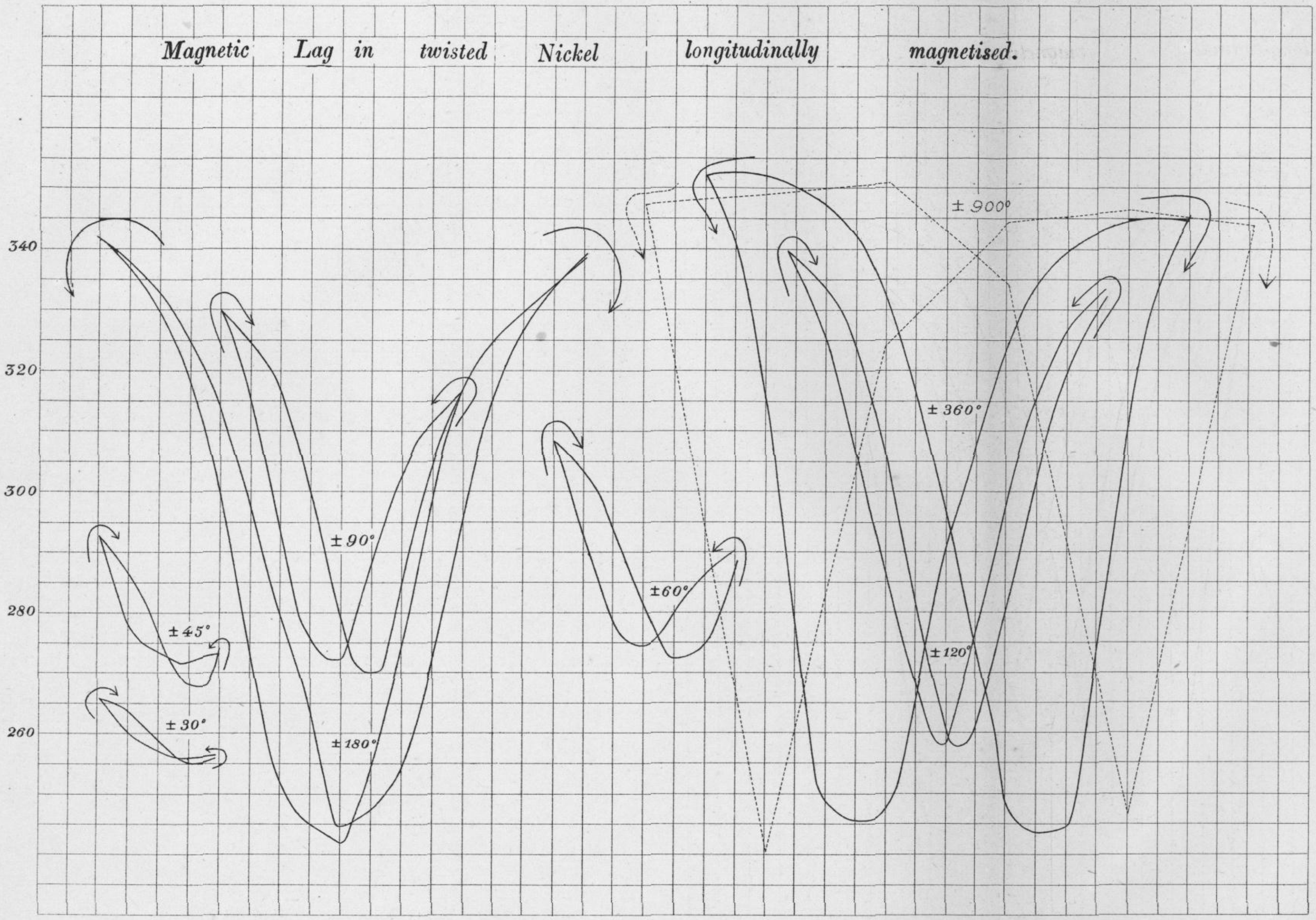

Magnetic Lag in twisted Nickel longitudinally magnetised.