PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

The Influence of Stress and Strain on the Physical Properties of Matter. Part I. Elasticity (continued). The Effect of Magnetisation on the Elasticity and the Internal Friction of Metals

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Phil. Trans. R. Soc. Lond. A 1888 **179**, 1-26
doi: 10.1098/rsta.1888.0001

PHILOSOPHICAL TRANSACTIONS.

I. *The Influence of Stress and Strain on the Physical Properties of Matter.*—Part I. *Elasticity* (continued).—*The Effect of Magnetisation on the Elasticity and the Internal Friction of Metals.*

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Received May 18,—Read May 27, 1886.
(Recast, with additions, December 16, 1887.)

Origin and Purpose of the Investigation.

According to Professor G. Wiedemann,[*] the main part of the internal friction which occurs in a torsionally vibrating wire is due to the rotation of the molecules about their axes, first to this side and then to that, as the wire vibrates to and fro. With this view the author's own experiments[†] on the internal friction of metals had been so far in accordance that he wished still further to test the matter by investigating the effect of magnetisation on the internal friction.

The author has already made some experiments on the effect of magnetisation on the torsional elasticity of metals,[‡] but the results of these experiments did not entirely satisfy him, inasmuch as the means of eliminating the heating effect of the magnetising solenoid were imperfect. It is true that the observed changes of temperature wrought by the solenoid were comparatively small, but so also was the apparent alteration of torsional elasticity due to magnetisation; and it seemed, therefore, advisable to reopen the inquiry, and to devise more perfect apparatus, whereby the heating effect above mentioned might be entirely done away with.

Description of Apparatus.

The wire was clamped at its upper extremity, a, into a **T**-shaped block of brass resting on the top of the air-chamber, A (see figure). The air-chamber consisted of two

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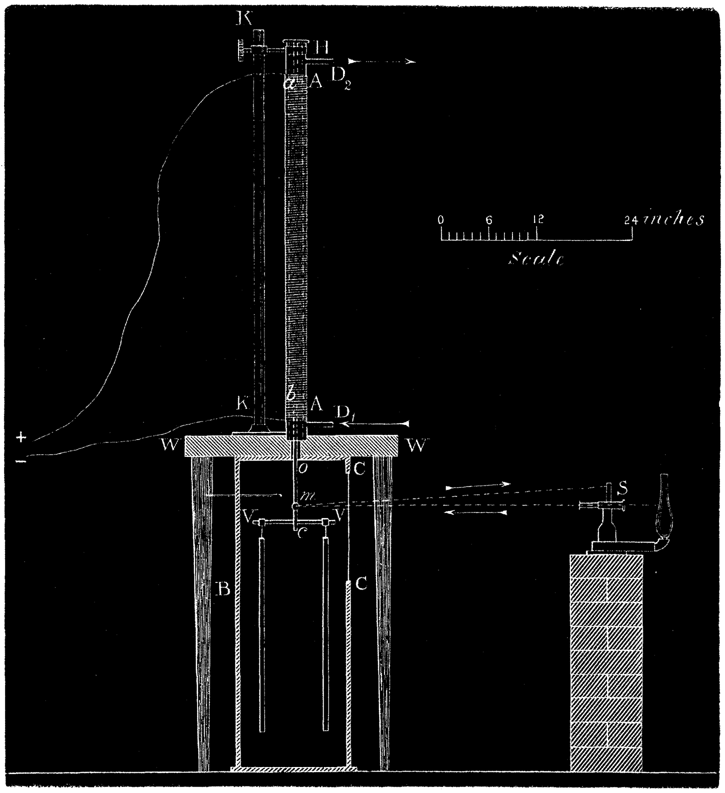
[*] 'Wiedemann's Annalen,' 1879, vol. 6, p. 485.

[†] 'Phil. Trans.,' 1886 (vol. 177, Part II.).

[‡] 'Phil. Trans.,' 1883 (vol. 174, pp. 34, 35).

concentric brass tubes, 4 feet in length, and enclosing between them an annular space, about a quarter of an inch thick, which could be filled with water. The wire hung vertically in the axis of the air-chamber, and at its lower extremity *b* was soldered to a copper rod, *b c*, about ·3 centim. in diameter, which was in turn connected to the horizontal bar, V V. From V V were suspended two cylinders of equal mass and dimensions, placed at equal distances from the axis of the wire. The nature of the cylinders and their mode of suspension to the bar V V have been described in a previous memoir on this subject.* The box B permits of free oscillation of V V and its appendages, and is provided with air-tight fitting doors, whilst the glass window, C, allows the vibrations of the wire to be measured by means of the usual mirror-lamp-and-scale arrangement, which is sufficiently shown in the figure. The base of the air-chamber, A, is let into the top of a stout wooden table pierced with a circular aperture, *o*, through the centre of which passes the rod *b c*; the top of the air-chamber is secured by a ring, H, clamped to the upright, K. Wrapped round the air-chamber, to within two or three inches of each end, was a considerable length of cotton-covered copper wire, $\frac{1}{20}$th of an inch in diameter, and well soaked with shellac varnish. The copper wire was wound round the chamber in one layer, thus forming a magnetising solenoid in which there were 8·25 turns in a centimetre; since the wire to be tested was well within the solenoid, the magnetising stress may be regarded as



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* 'Phil. Trans.,' 1886 (vol. 177, Part II.).

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

nearly constant throughout its entire length. In order to maintain the temperature constant, water from a large pail was made to flow into the annular space through the tube D_1 and out through the tube D_2 during the whole of the period of experimenting. The magnetising solenoid was actuated by ten GROVE's cells, the current from which passed through a resistance-box, a tangent galvanometer, and a commutator (not shown in the figure). The precautions adopted in the previous experiments were here reproduced, care being taken that the amplitude of the vibrations should be well within the limits of elasticity.

Experiment I.

An annealed iron wire, 100 centims. long and ·1 centim. in diameter. The current was always sent through the magnetising solenoid in the same direction,* and at least a hundred vibrations were allowed to take place, both when the solenoid was excited and when it was not, before the actual testing began. The experiment was carried on for two days for about six hours on each day, and the numbers given below for the logarithmic decrements and times of vibration are in each case the mean values resulting from 400 vibrations, first without excitation of the magnetizing solenoid, then with, then without, and so on.

First Day.

MAGNETISING solenoid not excited.

Number of trial.	Mean logarithmic decrement due to internal friction.†	Vibration-period in seconds.
1	·0009728	2·4745
3	·0009826	2·4790
5	·0009598	
7	·0009575	
MAGNETISING solenoid excited.		
2	·0010722	2·4750
4	·0011794‡	2·4745
6	·0010249	
8	·0010099	

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* Except in the fourth trial, when it was reversed for a few seconds by accident.

† The damping due to the resistance of the air has in all the experiments been calculated in the manner described in 'Phil. Trans.,' 1886 (vol. 177, Part II.).

‡ The current was in this trial put on, in the first instance, in the wrong direction, but was afterwards reversed while the trial was still going on; this, no doubt, accounts for the logarithmic decrement being larger than in the other trials.

Second Day.

MAGNETISING solenoid not excited.

Number of trial.	Mean logarithmic decrement due to internal friction.	Vibration-period in seconds.
2 4	·0009408 ·0009464	2·4765
MAGNETISING solenoid excited.		
1 3	·0010037 ·0010034	2·4740

The current used in the trials on both days was throughout fairly constant, the mean deflection of the needle of the tangent galvanometer being 47°. The constant of the tangent galvanometer was ·3167, therefore the magnetising stress in electromagnetic units was

$$4\pi \times 8{\cdot}25 \times \tan 47^\circ \times {\cdot}3167 = 35{\cdot}21.$$

This magnetising stress is a large one, and was, no doubt, sufficient to develop the greater part of the whole magnetism which the wire was capable of receiving. It may be seen that even under such a magnetising stress as the above the internal friction is not much altered; but, if the first four trials made on the first day be neglected, it appears that the internal friction is on both days greater by about $5\frac{1}{2}$ per cent. when the magnetising solenoid is excited than when it is not.

Having ascertained thus much, the author next proceeded to determine the effect of an intermittent magnetising stress, but still always in the same direction as before.

Experiment II.

One of the little clockwork arrangements used with Professor HUGHES'S induction balance was now put into the battery circuit, so that the latter could be rapidly opened and closed whilst the wire was vibrating, the same battery power being employed as before. In this case the logarithmic decrement was at first fairly constant, and equal to ·001442, showing that the internal friction was greater than when the circuit was not alternately opened and closed. After a time, however, as the clockwork began to run down, and the makes and breaks of the current in consequence to proceed more slowly, the value of the logarithmic decrement rapidly increased,[*] and finally became ·002719, or nearly double its first value.

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[*] The cause of the rapid increase is shown in Experiment VI.

Experiment III.

The current was reversed a number of times whilst the wire was vibrating, the reversals being timed by a pendulum vibrating once in a second; the same battery power as before was used.

Number of reversals of the current in 16 seconds.	Logarithmic decrement due to internal friction.
1	·001175
8	·004393
16	·003546

Experiment IV.

After the above reversals the magnetising stress was applied as in Experiment I., the battery power being still the same.

Magnetising solenoid not excited.

Number of trial.	Mean logarithmic decrement due to internal friction.	Vibration-period in seconds.
1 2 4	·0010891 ·0009730 ·0009551	
Magnetising solenoid excited.		
3	·0009569	
After a rest of 24 hours. Magnetising solenoid not excited.		
1 3 5	·0009480 ·0009071 ·0009363	2·4782 2·4790
Magnetising solenoid excited.		
2 4 6	·0009249 ·0009463 ·0009294	2·4785 2·4788

Experiment V.

The day after the last experiment had been made a fresh series of trials was instituted with currents of various strengths.

Number of trial.	Magnetising stress in C.G.S. units.	Logarithmic decrement due to internal friction.	Remarks.
1	0	·0009440	
2	4·615	·0094650	Current rendered intermittent by clockwork, but not reversed
3	4·615	·0034865	Current reversed every two seconds; no clockwork
4	0	·0010095	This trial made immediately after Trial 3, with only a few preliminary vibrations
5	0·104	·0009567	Current reversed every two seconds
6	0·035	·0009875	Ditto
7	0	·0009364	

Remarks on Experiments I.–V. inclusive.

It has been already noticed that when a large magnetising stress is used there is but a slight increase in the internal friction, provided the magnetising current is not interrupted or reversed during the trial, whilst Experiment IV. shows that if the current be previously reversed a great number of times even this small increase vanishes.* Accordingly, it may be said that under the conditions mentioned above the internal friction is quite independent of any *sustained* magnetic stress which may be acting on the vibrating wire. Similarly, there can be little doubt, the internal friction of a torsionally vibrating wire would be entirely independent of the amount of sustained statical torsional stress to which the metal might be at the same time subjected, provided the wire had been previously vibrated torsionally a great number of times.

The torsional elasticity is also equally independent of even large sustained magnetising stress, for it may be observed that the mean value of the vibration-period deduced from Experiment I. is for the magnetised iron 2·4745 seconds and for the unmagnetised iron 2·4767 seconds, whilst in Experiment IV. it is for the magnetised iron 2·47865 seconds and for the unmagnetised iron 2·47860 seconds. Other experi-

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* If we take the last six trials of this experiment, we get for the logarithmic decrements, when the magnetising solenoid is not excited, and when it is, the values ·0009305 and ·0009332 respectively; the difference between these two values lies within the limits of errors of observation.

ments, conducted most carefully, led to similar results, and abundantly established the above-mentioned independence.

When the magnetising current is interrupted, or when it is reversed whilst the wire is vibrating, there is for the larger magnetic stresses an increase of the internal friction which may become very considerable.*

Experiments II. and III. seem to prove that when the number of interruptions or reversals in a given time exceed a certain limit the effect produced by them on the logarithmic decrement begins to decline, but it would appear from Experiment II. that even when the interruptions occupy only a small fraction of a second† their effect in increasing the molecular friction is very sensible.

Experiment V. was made partly with a view of ascertaining how far the interrupted or reversed magnetic stress might be diminished before it ceased to exercise any perceptible influence on the internal friction. For the rather rapid interruptions produced by the clockwork it appears that when the magnetising stress is diminished to 4·615 its effect on the friction is nearly *nil.* This, however, is by no means the case when the current is reversed every two seconds, the value of the logarithmic decrement being then more than three times as great as it is when the wire is not magnetised; and even when the stress has been reduced to 0·104 it still exerts a sensible influence.

The experiments also show clearly that, at any rate for short periods of time, the longer the time of action of the magnetising stress, the greater is the effect on the internal friction, for otherwise in Experiment III. there would be a greater logarithmic decrement when the vibrations are 16 in 16 seconds than when the vibrations are 8 in 16 seconds, whereas the contrary is the case. Nevertheless, this increased effect on the internal friction which accompanies increased time of action does not extend beyond a period of a few seconds, for the increase of logarithmic decrement is considerably greater when the vibrations are 8 in 16 seconds than eight times the increase of logarithmic decrement when the vibrations are 1 in 16 seconds.‡

[*Added Sept. 29th*, 1887.—Experiment III. has shown that there is a definite frequency of reversal of magnetising stress for which the damping effect is a maximum, and it appeared to be of interest to ascertain more exactly what is the frequency producing the greatest effect with the particular wire examined, and also

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* See Experiments II. and III.

† The clockwork arrangement must have interrupted the current at least ten times in one second. [Later experiments showed that the diminution of the effect of an interrupted magnetic stress as the interruption-frequency increased arose from the fact that the difference between the vibration-frequency of the wire and that of the interruptions increased.]

‡ The increases of the logarithmic decrement are ·00346 and ·00024 in the two cases respectively. [September 25, 1887.—It was afterwards found that the results of Experiment III. are to be attributed almost entirely to differences between the vibration-frequency of the wire and the interruption-frequency.]

whether this special value represents a property of the material or is dependent on the accidents of dimensions of the wire and moment of inertia of the vibrator. An examination of the results recorded in Experiment III. seemed to indicate that the damping was a maximum when the vibration-frequency of the wire was the same as the reversal frequency. The following experiment was then made :—

Experiment VI.

A fresh piece of the same wire was tested with two different vibration-periods, the moment of inertia being altered by shifting the cylinders along the bar; the magnetising stress throughout was 46·025 C.G.S. units.

Interval in seconds between consecutive reversals of the magnetising stress.	Logarithmic decrement due to internal friction.	Vibration-period of the wire in seconds.
Before exciting the solenoid	·000799	2·370
1	·002841	
2	·004587	
3	·003988	
4	·001769	
½	·001052	4·725
1	·001785	
2	·003020	
3	·003871	
4	·004319	
5	·004470	
6	·002984	

The reversals of the magnetic stress were next made to synchronise with the vibrations of the wire, the vibration-period being 4·725 seconds.

Magnetic stress in C.G.S. units.	Logarithmic decrement due to internal friction.
46·88	·00896
77·35	·01118
107·40	·01137

This experiment speaks for itself, and shows most conclusively that the damping effect is a maximum when the reversal-period and the vibration-period synchronise.

The experiment also shows that, with these high values of the magnetic stress, the ratio of the logarithmic decrement to the magnetic stress diminishes very rapidly as the latter increases.

Hitherto the magnetic stress had been maintained during the whole period between one reversal and the next, but it was presently ascertained that if the magnetic stress be removed immediately after each reversal the damping is much increased.

Experiment VII.

A reversing key was used, such that the magnetising circuit could be opened the instant after each reversal;[*] the magnetising stress was 42·78 C.G.S. units; the vibration-period of the wire was 4·725 seconds, and with this the reversals were made to synchronise in one of the trials which were made.

Interval in seconds between consecutive reversals of the magnetising stress.	Logarithmic decrement due to internal friction.
4·000	·007986
4·725	·017416
5·000	·008759

On comparing these last results with those of Experiments V. and VI., it will be seen that when the battery circuit is opened instantly after each reversal the effect on the internal friction is twice as great as when the magnetic stress is maintained between each reversal and the next.

Nothing has been said as yet respecting the *phase* of the torsional vibrations of the wire at which the reversals of the magnetic stress were made. When the reversals synchronised with the torsional vibrations the former were made when the wire was *nearly*[†] at the end of its swing on one side or the other, but it was soon discovered that the effect of reversing the magnetic stress was greatest when the reversals took place *exactly* at the end of each swing, and least when they occurred at each instant the wire was passing its position of equilibrium.

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[*] The time during which the circuit remained closed after each reversal must have been only a small fraction of a second, as on reversing a sharp tap was given to the key, the spring of which was rather strong, and the finger removed as quickly as possible.

[†] That is, no particular pains had been taken to ensure that the reversals should take place *exactly* at the end of each swing.

Experiment VIII.

The vibration-period of the wire was made 4 seconds; the reversals synchronised with the vibrations of the wire, and the magnetising circuit was opened immediately after each reversal.

Magnetic stress in C.G.S. units.	Logarithmic decrement due to internal friction.
Reversals made at the end of each swing.	
1·135	·001080
42·775	·017416
Reversals made when the wire passed its position of equilibrium.	
1·135	·000796
42·775	·001432

The value of the logarithmic decrement when there was no magnetic stress acting on the wire was ·000782, or little less than when the reversals were made as the wire passed its position of equilibrium and the magnetic stress was 1·135. Even with the higher stress of 42·775 the effect of reversing when the wire was at the end of each swing is very considerably greater than when the reversals are made in the position of equilibrium.

In the next experiment an attempt was made to ascertain to what extent the magnetic stress could be reduced before it ceased to have any sensible effect on the internal friction.

Experiment IX.

The reversals were made to synchronise with the vibrations of the wire, and as exactly as possible when the wire had reached its extreme position on either side. The vibration-period of the wire was 4 seconds.

Magnetic stress in C.G.S. units.	Logarithmic decrement due to internal friction.
28·540	·018332
12·935	·016440
7·280	·008350
1·800	·001454
1·135	·001080
0·495	·000918
0·00	·000782

It is evident that, under the above circumstances, even when the magnetic stress is reduced to an amount which begins to be comparable with that of the earth's magnetic stress, there is a very appreciable damping due to the reversals.

By subtracting ·000782 from the numbers in the second column of the last Table, we get the *increase* of the logarithmic decrement due to the reversals in each case, and it is interesting to compare this increase with the stress producing it; this comparison is made below.

Magnetic stress. A.	Increase of the logarithmic decrement due to the reversals of the magnetic stress. B.	B : A.
28·540	·017550	·000616
12·935	·015658	·001210
7·280	·007568	·001040
1·800	·000672	·000374
1·135	·000298	·000262
0·495	·000136	·000274

The increase of the logarithmic decrement due to the reversals of the magnetic stress is, for small stresses, proportional to the latter. When the magnetic stress reaches 1·800 the friction increases in greater proportion than the stress, until the latter exceeds 12·935, when the ratio B : A begins to decline.* This is what might be expected from the behaviour of the magnetic permeability as the stress is gradually increased: in fact, with this particular specimen of iron, the permeability was found to increase very rapidly as the magnetic stress rose from 3 to 5 C.G.S. units, and again fell very rapidly when the stress rose from 12 upwards.

The damping effect of magnetic stress, when applied as above, is noteworthy for its magnitude; for the logarithmic decrement when the wire is subjected to reversals of a magnetic stress of 28·540 is actually between *twenty and thirty* times as great as when the wire is free from stress or under the influence of a sustained magnetising stress.†

Experiment X.

In this experiment the effects of reversals and of applying and removing the magnetic stress always in the same direction were compared together, the magnetic stress being in each case 42·775 C.G.S. units, and the vibration-period of the wire 4·725 seconds. In both cases the circuit was broken instantly after it was closed, and the reversals or closings were made to synchronise with the vibrations of the wire.

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* See also Experiment VI.

† Experiment II.

Logarithmic decrement due to internal friction when the magnetising stress was reversed.	Ditto when the magnetising stress was always applied in the same direction.
·017416	·006464

The effect in the former of the two cases is very much greater than in the latter, and this might have been anticipated, for the change of magnetisation with each reversal is much greater than that produced by each repetition of the stress. No doubt the difference in the effects in the two cases would be proportionately still greater for a lower value of magnetic stress, for, with this particular specimen of iron, when the magnetising stress was about 4 C.G.S. units, the change of magnetisation produced by each reversal was from eighteen to twenty times as great as the change produced by each repetition of the stress.]

It has been remarked that when the amplitudes of the vibrating wire are such as only to produce very small molecular displacements neither the internal friction nor the torsional elasticity is sensibly affected by sustained magnetisation. Since, however, the author's investigations, mentioned in the outset of this memoir, and in which the wire had been vibrated through comparatively large arcs, seemed to show that magnetism did slightly affect the torsional elasticity, he proceeded to re-try some of his old experiments relating to the effect of magnetisation on torsional elasticity, and at the same time also to study the alteration of internal friction which might ensue with large amplitudes of vibration.

Experiment XI.

The mirror was twisted round through an angle of 18°, then refixed; afterwards the vibrator was twisted so as to bring the reflected spot of light just on to one end of the scale; the vibrator was then let go, and as soon as the subsidence of the amplitude had caused the spot of light to reach the division on the scale marked 100,* or thereabouts, readings were taken. For the battery power 10 GROVE's cells were used, and the magnetising stress was very nearly 35 in electromagnetic units.

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* The zero of the scale was, in this instance, at the end of the scale from which the vibrator was started, so that as the amplitudes of the vibrations subsided the readings increased.

MAGNETISING solenoid not excited.

Number of trial.	Reading when the vibrator had reached its extreme position.	Number of vibrations executed after the readings had commenced.
1	102 608	0 52
2	108 608	0 52
3	100 600	0 52
4	98 389	0 20
Magnetising solenoid excited.		
5	101 709	0 52
6	101 500	0 20

Thus it appears that, whether the subsidence in 52 or in 20 vibrations be considered, the internal friction is very perceptibly greater when the solenoid is excited than when it is not,* and that the difference is greater, the greater the mean amplitude of vibration.

Experiment XII.

With the same arrangement as in the last experiment, and with the same initial arc of vibration, the following was found to be the effect of sustained longitudinal magnetisation on the vibration-period, the battery power used being the same as before.

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* The subsidence for 52 vibrations when the solenoid is excited is 608, and when the solenoid is not excited 500, the former being 21 per cent. greater than the other. Again, the subsidence in 20 vibrations is 36 per cent. greater when the solenoid is excited than when it is not excited.

MAGNETISING solenoid not excited.

Number of trial.	Vibration-period in seconds.
1 2	2·481 2·479
Mean	2·480
Magnetising solenoid excited.	
3	2·483

From this last experiment it would seem that for these comparatively large amplitudes the vibration-period is slightly greater for the magnetised than for the unmagnetised wire, and that consequently the results previously obtained by the author with less perfect apparatus are so far confirmed.

The Limit of Magnetic Elasticity.

From Experiment V. it is evident that when the value of the magnetising stress becomes as small as 0·104 the effect of continued reversals of it on the internal friction is still perceptible. Now, as any such effect was attributed to *permanent* * twist imparted to the molecules, first to this side and then to that, according to the direction of the magnetising current, an attempt was made to ascertain how far the magnetic stress might be increased from zero upwards before the molecules would be permanently twisted by it.

Experiment XIII.

In the axis of a magnetising solenoid 11·43 centims. in length was placed a bundle of well-annealed iron wires, consisting of twenty pieces, each 8 centims. in length and ·1 centim. in diameter. The axis of the magnetising solenoid was coincident with that of a second solenoid, made up of 814 turns of cotton-covered copper wire; the second solenoid surrounded the first, and was connected up with a very delicate THOMSON'S reflecting galvanometer. A single GROVE'S cell, with a box of resistance coils in circuit, actuated the magnetising solenoid, and the magnetism imparted was measured by the throw of the needle of the galvanometer produced by the induced current which resulted on closing the battery circuit. The permanent

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* The word "permanent," whenever used in this memoir in connection with strain, must be taken as denoting merely that the strain does not *immediately* disappear on the removal of the stress. The author believes that such strains as have occurred in his experiments are for the most part *sub-permanent.*

magnetism for a given magnetic stress was measured by the difference between the deflections which ensued when the battery circuit was closed for the first and for the tenth times; thus, if D_1 and D_{10} be these two deflections respectively, the permanent magnetism is assumed to be measured by $D_1 - D_{10}$, and the temporary magnetism by D_{10}.

Resistance in the battery circuit in B.A. units R.	Permanent magnetism $D_1 - D_{10}$.	Temporary magnetism D_{10}.	$(D_1 - D_{10})$ R.	$D_{10} \times$ R.
1002*	0	4	0	40×10^2
502	0	8	0	40 ,,
302	0	15	0	45 ,,
202	1·1	23	$2·2 \times 10^2$	46 ,,
152	2·0	31	3·0 ,,	47 ,,
102	3·5	49	3·6 ,,	50 ,,
82	5·2	62	4·3 ,,	51 ,,
62	8·3	88	5·1 ,,	55 ,,
42	19·0	137	8·0 ,,	58 ,,
32	31·8	188	10·2 ,,	60 ,,

From this experiment it appears that until the resistance in the battery circuit has become about 302 B.A. units there is no perceptible permanent magnetism. The electromotive force of the GROVE's cell was 1·9 volts; the number of turns per centimetre in the magnetising solenoid was $\frac{70}{11·43}$, and the total resistance in circuit was $302 \times ·9889$ legal ohms. The magnetising stress in electromagnetic units would consequently be

$$\frac{4\pi \times 1·9 \times 10^8 \times 70}{302 \times ·9889 \times 10^9 \times 11·43},$$

or

$$·04896.$$

The above magnetic stress is little more than one-fourth of that due to the horizontal component of the earth's magnetic force. The magnetising solenoid was in this experiment placed horizontally and at right angles to the magnetic meridian, so that the iron was uninfluenced by the magnetism of the earth; but other similar experiments seemed to show that, in whatever position the iron was placed, the molecules required a very appreciable magnetic stress to produce permanent molecular set.†

[*October* 6*th*, 1887.—It may be objected to the above experiment that the length of the pieces of iron is not sufficiently great in comparison with their diameter;‡ but

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* The resistance of the battery and solenoid amounted to 2 B.A. units, which together with 1000 B.A. units added from the box makes the number here given.

† Later experiments, however, proved that even with the small magnetic stress quoted above a permanent deflection *is* produced. (See the passage following.)

‡ *Cf.* EWING, 'Phil. Trans.,' 1885, pp. 533–536.

the following experiment shows that even when the length is so great as to render such an objection quite out of the question there is an *apparent* limit of magnetic elasticity.

Experiment XIV.

A magnetising solenoid, no less than 354·3 centimetres in length, was prepared, having coiled on it, in a single layer, silk-covered copper wire; the number of turns per centimetre was 8·5. The secondary coil consisted of 5909 turns of silk-covered copper wire, coated with shellac varnish, laid on in six layers; the resistance of this coil was nearly equal to that of the ballistic galvanometer. The bundle of iron wires was increased in number to 40, and the length of each was 325 centimetres, so that, regarding the bundle as one solid rod, the length of it was 512·5 times the diameter. The mode of experimenting was the same as before.

Magnetising stress in C.G.S. units S.	Permanent magnetism in scale divisions $D_1 - D_{10}$.	Temporary ditto D_{10}.	$D_{10} : S$
0·00153	0·0	8·0	5229
0·00306	0·0	15·5	5074
0·00760	0·0	39·0	5134
0·01506	0·0	78·0	5180
0·01874	0·0	96·0	5124
0·02480	0·0	128·8	5193
0·02960	0·0	153·7	5194
0·03667	0·5	190·4	5193
0·04821	2·5	250·8	5202
0·05720	4·0	297·5	5201

In reading the deflections there was certainly no error equal to ·5 of a division, and the first *trace* of the molecules taking a permanent set is when the magnetic stress has reached 0·03667, or about one-fifth of the value of the horizontal component of the earth's magnetic force. The first *decided* permanent set does not apparently occur till the stress has reached 0·04821, a value very close to that recorded in the last experiment as the limit of magnetic elasticity.

A similar experiment to the above was tried with a wrought-iron rod in an unannealed condition, and in this case there was not the slightest trace of permanent set until a stress of 0·04821 was reached, whilst the deflection due to temporary magnetisation with this stress was 538 scale-divisions.

These last experiments *seem* to show that between the values 0 and $\frac{1}{5}$H of magnetic stress there is *no permanent set whatever;* but in the next experiment it will appear that, if we operate by the method of reversals, permanent set may be detected with much smaller stresses.

Experiment XV.

The bundle of soft-iron wires used in Experiment XIV. was subjected to gradually increased amounts of magnetic stress according to the following plan :—First the magnetising circuit was closed and the deflection D_1 noted, and after the spot of light had come to rest the circuit was opened and the deflection D_2 observed ; next the battery was reversed, and the deflections D_3, D_4, produced by closing and opening the circuit respectively, were read off as before. When the magnetic stress produces no permanent set the four deflections are all of equal value ; but, if any such set exists, $D_3 - D_4$ will represent the change of magnetisation produced by the wrenching of the molecules from their positions of permanent set on one side to their positions of permanent set on the other. If the reversals be made a great many times, $D_3 - D_4$ becomes less and less, but never vanishes, and finally becomes a constant. Experimenting in the manner mentioned above, the permanent set could be just detected when the magnetic stress had reached the value of 0·01690, a value only a little less than half of that at which it had been detected by the other method.* The method of reversals possesses two great advantages over the previous method in attacking the question of a magnetic elastic limit. In the first place the amount of permanent set detectable is about doubled ; and, in the second place, we may go on repeating the reversals so that any failure to detect a small amount of permanent set at the first reversal may be rectified in the second or subsequent reversals.

A very protracted examination of the values of $D_3 - D_4$ for different values of magnetic stress extending beyond $\frac{1}{5}$H was now made,† and it was found that, provided the reversals were for each stress continued long enough to make $D_3 - D_4$ constant, the permanent set as thus measured was exactly proportional to the square of the magnetic stress. We can now plainly see how matters stand with respect to a magnetic elastic limit, namely, that no such limit is mathematically existent ; but from the rapid falling-off of the permanent set, with decrease of magnetic stress, as indicated by the above-mentioned law, and from the observations with hard and soft iron which have been already made, we may, in all probability, safely assume that even with the very softest iron‡ no permanent set amounting to one per cent. can be detected by the ballistic method, provided the magnetic stress does not exceed $\frac{1}{5}$H.§]

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* This might be expected from what has been said above.

† It is not necessary to enter into the details of this examination, as they will be laid before the Royal Society in a subsequent paper.

‡ The soft-iron wire used in these experiments was specially prepared for the author by Messrs. JOHNSON and NEPHEW ; it can be permanently elongated 25 per cent. before breaking.

§ Before this note was written Lord RAYLEIGH had by another method shown ('Phil. Mag.,' vol. 23, 1887, pp. 225–241) that up to $\frac{1}{5}$H there is no sensible permanent set. Lord RAYLEIGH has also shown in his paper that when permanent set is produced by higher magnetising stresses the amount of set is proportional to the square of the stress.

The Effect on the Internal Friction and on the Torsional Elasticity produced by an Electric Current.

Experiment XVI.

Some experiments made in the year 1880* had seemed to show that, unless an electric current was very powerful, its influence on the torsional elasticity of iron and copper was very nearly, if not quite, *nil*; and even in those cases where, apparently, slight changes were wrought by powerful currents the results were such as to leave the question undecided as to whether these changes might be due, not directly to the current, but rather to the consequent heating. Accordingly the author determined to dispense with powerful currents, and to endeavour to compensate for the lessening of the current by increasing the accuracy and number of the observations. The following were the arrangements:—

The clamp which secured the upper extremity of the wire was provided with a terminal screw, by means of which connection was made with one pole of a battery of five cells of the Leclanché type.† To the bar of the vibrator attached to the lower extremity of the wire was soldered a rather fine sewing needle, which, hanging vertically downwards in a line which was a continuation of the axis of the wire, dipped with its point into a cup filled with mercury, whilst a caoutchouc-covered connecting wire, passing from the cup through a key and a tangent-galvanometer to the other pole of the battery, served to complete the circuit. It having been ascertained that the rotation of the fine point of the needle in the mercury did not appreciably increase the logarithmic decrement, the effect of the current on the internal friction and the torsional elasticity of wires of nickel, iron, and tin was investigated. As the lengths of the wires used were in all cases more than 600 centimetres‡, and the diameters comparatively small, the strength of the current did not exceed 0·30 ampère. It will be hardly necessary to enter further into details, since these experiments resemble very closely those already described, when the effect of longitudinal magnetisation was tested. Suffice it that the examination of the wires occupied several days, and the final conclusion arrived at was that when the current was maintained constant there was no effect on the internal friction or on the vibration-period produced by it apart from what might be expected from the very slight rise of temperature resulting from the passage of the current,§ which rise could not in any case have equalled 1° Centigrade.

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* 'Phil. Trans.,' 1883 (vol. 174, Part I). Experiments 24 and 25.

† The current yielded by this battery did not vary so much as 5 per cent. during the whole of the period of experimenting.

‡ The apparatus here used was described in the author's first memoir on Internal Friction.

§ This could be calculated within a sufficient degree of approximation from data furnished br Mr. J. T. Bottomley ('Nature,' Sept. 25 and Oct. 2, 1884).

It may be objected to the above experiments that too weak a current was employed to bring out with sufficient distinctness any sign of what was looked for; but, as has been already mentioned, the reason for employing such a current was to avoid as far as possible heating effects. Moreover, it was evident that the nickel and iron wires were in a state of circular magnetisation under the influence of the current, inasmuch as a very sensible twist was produced by the combined action of the circular magnetisation and the longitudinal magnetisation, resulting from the vertical component of the earth's magnetic force. The current passed *up* the wires, and by the earth's vertical magnetic force they were longitudinally magnetised with the north-seeking magnetic pole downwards, the combined action of the two magnetising stresses resulting in twisting the nickel wire in the direction of a right-handed screw;* by properly timing the impulses of the key used for closing the circuit a deflection of eight scale-divisions could be easily produced. With the iron wire the twist was much more perceptible than with nickel, and in the *opposite* direction, as might be expected from the researches of JOULE and GORE. By properly timing the impulses of the key an amplitude of no less than 140 scale-divisions could be got up.

Experiment XVII.

[*October*, 1887.—It has been remarked that a *sustained* electric current passing through a wire does not, except by heating, appreciably alter the internal friction. The currents used in bringing out this result, though strong enough to produce very sensible circular magnetisation, were comparatively feeble. As soon, however, as it appeared, from Experiment VII., that the magnetising stress need only be applied for an instant in order to produce an effect, it was resolved to ascertain to what extent the internal friction could be influenced by circular magnetisation produced by sending an intermittent current through the wire, the current being reversed in synchronism with the torsional vibrations of the wire at the end of each swing of the latter, and instantly removed again after each reversal. The vibration-period of the wire was 4·725 seconds.

Current in C.G.S. units used to circularly magnetise.	Logarithmic decrement due to internal friction.
0·0000	·000845
0·0199	·001102
0·0345	·001210
0·0616	·001564
0·1060	·002624
0·2056	·004591

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* This shows a shortening in the direction of magnetisation, and therefore the result is in accordance with that arrived at by Professor BARRETT, who has proved that nickel contracts in the direction of magnetisation.

By subtracting ·000845 from the other numbers in the same column we obtain the *increase* of logarithmic decrement due to the reversals of the current in each case.

Current in C.G.S. units. A.	Increase of logarithmic decrement due to reversals. B.	B : A.
0·0199	·000257	·0129
0·0345	·000365	·0106
0·0616	·000719	·0117
0·1060	·001779	·0168
0·2056	·003746	·0237

The increase of the logarithmic decrement increases proportionately to the current until the latter attains a value of 0·0616; from this point upwards the ratio B : A increases. Since the circuit was broken immediately after each reversal the current might have been carried much higher without sensibly heating the wire,* and, in all probability, with circular magnetisation as with longitudinal magnetisation, the ratio B : A would, beyond a certain value of the magnetising stress, begin to decrease as the stress increased. There was, however, the following difficulty in experimenting with higher currents :—In consequence of the wire hanging vertically it was all the time under the influence of the earth's vertical magnetic stress, and was thereby longitudinally magnetised, so that when the current was sent up or down the wire the combination of the two magnetisations caused the wire to twist to this side or that; and, since the reversals of the current were synchronous with the vibrations of the wire, the amplitude of these last vibrations was, owing to the above-mentioned cause, increased or diminished according as the phases of the two sets of vibrations were the same or opposite. With the smaller currents the difficulty was sufficiently overcome by first making a number of reversals with the two sets of vibrations in the same phase, and then an equal number with the phases opposed; but with the current 0·2056 this mode of compensation began to fail. It is evident, however, that the internal friction of iron can be very largely increased by reversals of a current passing through the wire.]

The Effect of Magnetisation on the Longitudinal Elasticity.

According to GUILLAUME WERTHEIM† *long continued* magnetisation diminishes both temporarily and permanently the longitudinal elasticity of iron and steel, but magnetisation continued only for a short time has no sensible effect. Since the author's own experiments led him to view with considerable caution these results of M. WERTHEIM, and to believe that *long continued* magnetisation diminished the elasticity

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* Rise of temperature causes *decrease* of the internal friction of annealed iron.

† 'Annales de Chimie,' vol. 12, 1844, p. 610.

simply on account of the heat generated by the magnetising solenoid, he proceeded as follows:—

Experiment XVIII.

The magnetising solenoid described in the first portion of this memoir was placed horizontally, and an iron wire of rather more than twice the length of the solenoid was stretched along the axis of the latter and fixed at both ends. Water, as in the earlier experiments, was kept constantly flowing through the annular space of the air-chamber, so as to prevent the heat generated in the solenoid from affecting the wire. The wire, when rubbed along its length with a resined glove, gave a clear note, which was taken on a monochord. The magnetising solenoid was now excited by ten GROVE's cells, and the wire, having been loosened and stretched by the same load as before,* was again secured at the ends and rubbed. The note yielded was precisely the same as before, and, though the current was allowed to flow through the solenoid for some time, not the slightest change could be detected. Several trials were made of the same kind, and all concurred in yielding the same results. Of course, the value to be attached to an experiment of this kind depends mainly upon the ability of the observer to distinguish small differences of pitch. Now the author's assistant† has so frequently proved his skill in this respect‡ that it can be fairly said that if longitudinal magnetisation does influence longitudinal elasticity it does so to an extent which cannot be appreciated, even by a well-trained ear, when tested in the above manner. It might, perhaps, be possible to detect some effect of magnetisation on the temporary elongation produced by *large* loads when the method of static extension is employed, but not with the arrangement used by WERTHEIM. M. WERTHEIM seems to have taken no precautions to avoid the heating effects of the magnetising solenoid, and the very fact that he was only able to detect any change after the solenoid had been excited *for some time* points suspiciously to heating as being the origin of what he observed. It is true that according to WERTHEIM the longitudinal elasticity of iron is increased by a small rise of temperature, but in this the author has ventured to differ from him.§

The Influence of an Electric Current on Longitudinal Elasticity.

According to WERTHEIM‖ the longitudinal elasticity of wires is diminished by the passage of an electric current, independently of the alteration which would result

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* The full arrangement for effecting this will be described in a future paper.

† Mr. FURSE, the Curator of the Museum of King George III., King's College, Strand.

‡ The author has already given ('Phil. Trans.,' 1883 (vol. 174, Part I.), p. 53 and elsewhere) specimens of this.

§ 'Phil. Trans.,' 1883 (vol. 174, Part I.), pp. 128–131.

‖ 'Annales de Chimie,' vol. 12, 1844.

from the elevation of temperature produced by the current. When, however, the experiments were concluded which have just been recorded, and, moreover, no appreciable effect had been found to be produced on the torsional elasticity by the passage of a current, the author was led to endeavour to ascertain how far WERTHEIM might be justified in the above-mentioned conclusion as regards the effect of a current on the longitudinal elasticity.

First, in order to avoid heating as much as possible, currents from ·2 to ·3 ampère were employed—currents which, though comparatively weak, are, as has been shown, capable of producing very sensible circular magnetisation. The same length of wire and the same apparatus as that described in the author's former papers on Elasticity* were used, with this difference, however, that now the wire to be examined and the comparison-wire were secured at their upper extremities to separate clamps which were insulated from each other and from the bracket on which they rested. Near their lower extremities the wire and the comparison-wire were united by a short piece of copper wire, so that the current from the battery might, after passing through a tangent-galvanometer and a commutator, continue its course down one wire and up the other to the other pole of the battery. By this arrangement it may be seen that the heating effect of the current will not cause any error except that due to slight difference in the thermal expansibility of the wire and the comparison-wire, due to the difference in the load on the two wires.† Any change of elasticity wrought by the current, amounting to ·1 per cent., could have readily been detected, but after some five or six hours had been spent, and loads of very different amounts, almost up to the breaking-load of the wire, used, the attempt was abandoned, as it seemed certain that for these comparatively small currents there was no appreciable change in the elasticity resulting from the passage of the current when the latter was maintained constant.

Next the effect of much more powerful currents was tried, the same arrangements being employed as in Experiment XVIII., with the exception that the magnetising solenoid was removed, and in its place two terminal screws substituted, one near each end of the wire, but, of course, beyond the points where the wires are clamped. These terminal screws served to connect the wire with a battery of 10 GROVE's cells and a box of resistance-coils, together with a tangent-galvanometer and commutator. The wire was rubbed along its length with a resined glove, and the pitch of the note determined by means of the syren—first when the current was not passing through the wire, next when it was, and finally, a second time, with no current. The following were the results obtained with annealed iron wire and unannealed piano-steel wire :—

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* 'Phil. Trans.,' 1883 (vol. 174, Part I.), pp. 2–4.

† Even this source of error can be eliminated by testing the wire, in the first place, with the permanent load on the comparison-wire greater, and in the second place less, by an equal amount than that on the wire to be examined.

Experiment XIX.

IRON wire 365 centimetres in length and ·07035 centimetre in diameter.

Current in C.G.S. units.	Calculated rise of temperature in degrees Centigrade produced by the current.	Number of longitudinal vibrations in two minutes.	Decrease of longitudinal elasticity per unit per degree rise of temperature.
0	—	4115·5 × 20	—
0·323	45·31	4085·0 × 20	·0003268

Experiment XX.

PIANO-STEEL 365 centimetres in length and ·0824 centimetre in diameter.

Current in C.G.S. units.	Calculated rise of temperature in degrees Centigrade produced by the current.	Number of longitudinal vibrations in two minutes.	Decrease of longitudinal elasticity per unit per degree rise of temperature.
0	—	4255·3 × 20	—
0·2335	44·67	4229·5 × 20	·0003020

The principal difficulty connected with the accurate reduction of these experiments lies in the calculation of the rise of temperature produced by the current. According to J. T. BOTTOMLEY[*] the rise of temperature may be obtained from the following easily proved formula :—

$$t - \theta = \frac{4c^2\sigma_t}{J\pi^2 d^3 e},$$

where t is the temperature of the wire, θ the temperature of the room, c the current, σ_t the specific resistance of the wire at the temperature t, J JOULE'S equivalent, d the diameter of the wire, and e the emissivity of the wire. It would follow from Mr. BOTTOMLEY'S experiments that with wires whose diameters vary from 0·085 centimetre to 0·040 centimetre the value of e ranges from $\frac{1}{2000}$ to $\frac{1}{400}$, or approximately as the inverse of the square of the diameter. On this last assumption the values of e for the iron and steel wires were calculated to be $\frac{1}{1356}$ and $\frac{1}{1879}$ respectively. The values of σ_t were calculated from a knowledge of the specific resistance of the two metals at the temperature of the room, which was 18° C., and of the coefficient of increase of resistance per degree rise of temperature. The specific resistances of the iron and steel wires at the temperature of 18° C. were 9707 and 20,742 respectively,

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[*] 'Nature,' September 25 and October 2, 1884.

and the coefficients of increase of resistance were approximately ·005 and ·004 respectively. The value of J was assumed to be 42,000,000.

The liability to error in the estimation of the number of vibrations executed by the wire in a given time is comparatively small, and is certainly much smaller than that arising from uncertainty as regards the emissivity. On the whole, then, it is only safe to assume that, if the observed decrease of the longitudinal elasticity of the iron and steel be *entirely* due to the rise of temperature caused by the current, this decrease would be about ·0003 per unit per degree Centigrade rise of temperature. Now, as far as the author is aware, there have been no investigations of the effect of rise of temperature on the longitudinal elasticity of iron and steel as determined by the method of vibrations. The author has, however, by the method of static extension, obtained for unannealed piano steel, and for soft iron, a decrease of longitudinal elasticity per unit, resulting from a rise of 1° Centigrade, of between ·0002 and ·0003.* Further, he has recently obtained from experiments on torsionally vibrating iron wire at various temperatures a decrease of torsional elasticity amounting to ·0003 per unit per degree Centigrade rise of temperature. Taking all these facts into consideration, it seems probable that such effects as are produced by even powerful currents on the longitudinal elasticity are solely to be ascribed to the heat generated by these currents.

Discussion of WIEDEMANN'S *Theory respecting the Internal Friction of Metals.*

It will be now advantageous to review very briefly some of the results recorded in this and the author's two previous memoirs on the internal friction of metals, with the object of ascertaining how far these results support WIEDEMANN'S ingenious theory respecting the cause of the friction. According to WIEDEMANN, as the wire vibrates torsionally in one direction or the opposite, so do the molecules rotate about their axes in one direction or the opposite, and at each rotation are *permanently* deflected, so that, if at the extremity of any one of the swings of the vibrator the latter could be checked and afterwards quietly restored to its position of equilibrium without allowing it to pass over to the other side, the molecules would be permanently deflected. If, however, as in free torsional vibrations, the vibrator is allowed to pass over the position of equilibrium, the molecules will be permanently twisted in the opposite direction, and so on; thus the loss of energy due to internal friction represents the work which has to be performed in order to twist the molecules from their permanent positions on the one side to their permanent positions on the other. WIEDEMANN founds his theory mainly on the results of his experiments on the torsion experienced by wires as tested by the statical method. In these experiments he finds that even the slightest torsional stress produces permanent torsion of the wire, and also, as he *assumes*, permanent twist of the molecules. It will be as well

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* 'Phil. Trans.,' 1883 (vol. 174, Part I.), pp. 132–133.

to quote one of WIEDEMANN'S experiments, so that some idea may be formed of the extent of the permanent deformation produced by a given torsional stress.

Experiment XXI.

An annealed brass wire 48 centims. in length and 2 centims. in diameter, loaded with 10·46 kilos., and subjected to torsional stress, increased by small amounts at a time. Scale and mirror were used, and a displacement of the image through 34·9 scale-divisions corresponded to 1° of rotation of the mirror.

Load in grammes used in producing the torsion W.	Total torsion immediately produced, T.*	Total torsion produced after some time, T_1.*	Total permanent torsion produced after some time, P_1.
1st 30	104 × 3	104 × 3	0·6
Next 10	104	104	0·7
Ditto	·107	107	1·0
Ditto	105	105	1·5
Ditto	105	106	2·0
Ditto	111	111	4·0
Ditto	112·5	114	6·2

An examination of the fourth column shows that the consecutive values of permanent deformation produced by consecutive equal loads form roughly a geometrical progression, of which the common ratio is 1·42. It may then be roughly calculated that the permanent twist produced by the *first* 10 grammes cannot be greater than ·14, whilst the total torsion is 104. Thus in this experiment the permanent torsion produced by the smallest load is less than $\frac{1}{700}$th of the total; but in some of the author's own experiments, in consequence of a much greater length of wire being used, and that, too, of much smaller diameter, the temporary deformations vary, on the average, between $\frac{1}{25}$th and $\frac{1}{80}$th of the *smallest* in WIEDEMANN'S experiments, so that the permanent torsion of *the wire itself* would escape observation should the attempt be made to detect it by the method of statical torsion.

[*October*, 1887.—Nevertheless, the experiments described in the author's paper seem to place beyond doubt the soundness of WIEDEMANN'S hypothesis that even with the most minute torsional deformations the *molecules* of a torsionally oscillating wire are permanently twisted first to this side and then to that, and that this is the main cause of the internal friction.[†] For how else can the enormous increase of the internal friction which can be effected by interrupted magnetisation be accounted for? Had a magnetic elastic limit been proved to exist, there would have been some little difficulty in accepting WIEDEMANN'S views, for in the author's experiments on internal friction, previously alluded to, the logarithmic decrement was found to be independent

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[*] WIEDEMANN designates as *temporary* torsion what is here put down as total torsion.

[†] Provided the amplitudes of the oscillations do not exceed a certain limit.

of the amplitude even for the very minutest torsional deformations; but, since it has been proved that any magnetic stress, however small, must produce some molecular permanent set, the difficulty vanishes.]

Summary.

1. When the deformations produced by the oscillations are small the internal friction of a torsionally vibrating wire is not affected by sustained longitudinal magnetisation of moderate amount. The internal friction is also not affected by sustained magnetisation, even when carried nearly to the point of saturation, provided the magnetising current be, previously to experimenting, reversed a great number of times.

2. When the deformations are large the internal friction is increased by sustained magnetisation of large amount.

3. The torsional elasticity is entirely independent of any sustained longitudinally magnetising stress which may be acting upon the wire, provided the deformations produced by the torsional oscillations be small. When the deformations are large the torsional elasticity is very slightly decreased by sustained longitudinal magnetisation of large amount.

4. When the magnetising current is interrupted, and, to a greater extent, when it is reversed repeatedly whilst the wire is oscillating, the internal friction is increased provided the magnetising stress be of moderate amount. The increase of internal friction may become very considerable when the magnetising stress is great.

5. When the deformations produced by the oscillations are small the torsional elasticity is not affected by either repeatedly interrupted or reversed magnetisation, even when the magnetising current is very large.

6. There exists a limit of magnetic stress within which the magnetic elasticity is *sensibly* perfect, but a mathematically true magnetic elastic limit does not exist.

7. The passage of an electric current through a torsionally vibrating wire does not affect, except by heating, either the internal friction or the torsional elasticity, provided the deformations produced by the oscillations be small.

8. The effect of longitudinal magnetisation, even when carried to the point of saturation, on the longitudinal oscillations of an iron or steel wire is *nil.*

9. The passage of an electric current through a longitudinally oscillating iron or steel wire does not, except by heating, affect the oscillation-frequency.

10. When the deformations produced in a torsionally oscillating wire do not exceed a certain limit the internal friction mainly depends upon the *sub-permanent* rotation to and fro of the molecules about their axes.