The effect of an electric current upon the elasticity of wires

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THE EFFECT OF AN ELECTRIC CURRENT
UPON THE
ELASTICITY OF WIRES

By H. L. Dodge

Thesis presented
to the
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At least as early as 1844 an attempt was made to discover the effect of the electric current upon Young's modulus. Wertheim (Wiedemann's Elektricitat, II, 218) using wires of gold, iron, steel, and silver, stretched by means of weights found a decrease in Young's modulus due to the presence of current. He also found that the passage of current lowered the pitch of the musical tones from stretched wires. It would seem as if these effects could be best accounted for through the heating effect of the current, but Wertheim is quite emphatic upon this point saying that this could not be the case since the wires immediately upon the removal of the current assumed their former elasticity.

Edlund (Annal. d. Phys. 129, 15, 1866) was not satisfied with Wertheim's results. He made allowance for the temperature effect of the current measuring the temperature by the change in resistance.
of the wire itself. His conclusion was that the current, except for the temperature effect does not change Young's modulus. On the other hand he found that there is an additional lengthening due to current, over and above the expansion due to temperature, the increase in length due to the pure current effect being equal to the effect of an increase in temperature of from one to nine degrees Centigrade. The following year Edlund (Annal. d. Phys. 131, 337, 1867) reports having found a source of error in the former method. His new observations result however in the very same conclusions.

Streintz (Annal. d. Phys. 150, 368, 1873) feeling that the results of Wertheim and Edlund were somewhat contradictory, made the wires which he studied part of a torsion pendulum. He found changes in Young's modulus as given below, the numbers showing by what per cent of the change due to temperature is
the effect in the case of current greater than the pure temperature effect. Observations were taken at room temperature and at 55.5°C. (melting point of stearine). Results: Brass (a), -5.9; (b), +12.6; Copper, 0.0; Silver, +3.9; Iron, +3.1; Steel, -12.2. It is a little surprising to find Streintz taking the average (0.3) and from it concluding that there is no change in Young's modulus due to current. Another series of experiments showed an increase in length due to current as had been found by Edlund.

Mebius (Wiedemann Elektricitat. II, 220) employing rods of steel, iron, brass, and silver, and using the method of bending found the change in the elasticity of the respective rods to be less than 0.00089, 0.0015, 0.0047, 0.0037 per cent.

Miss Hoyes (Phys. Rev. II, 279, 1895) using steel piano wires mounted horizontally upon a dividing engine secured rather consistent results
when the wires were heated externally but no regularity in the case of current heating. The following year (Phys. Rev. III, 433, 1896) with a somewhat improved apparatus and using steel, silver and copper wires she reached the conclusion that except for the heating effect current has no effect upon Young's modulus. An inspection of her results leads one to question whether they justify this conclusion for although according to the report each measurement was made with great care the plotted results indicate a very great experimental error.

Walker (Proc. Roy. Soc. Edin. 27, 343, 1907) following identically the same plan as Miss Noyes except that he used resistance to measure temperature (a method abandoned by Miss Noyes) found very irregular changes. A small current caused a decrease in the modulus in the case of steel, soft iron, and copper. This was not observed in the case of platinum.
Further increase in current resulted in a rapid increase in Young's modulus to a maximum value, followed by a decrease to about the original value. Upon cooling a maximum value was passed but the values of the modulus for decreasing current were considerably different from those for increasing. A more critical detailed discussion of the work of previous investigators is unnecessary here. It is evident that their results lead to no satisfactory conclusion. The writer upon careful examination of the literature arrived at the opinion that the inability of the investigators to secure consistent results or of any single investigator to secure results of unquestionable value was due to the use of apparatus and methods which introduced gross errors.

It was his conclusion that the working assumption should be that the changes in Young's modulus have some system and that inconsistent results should be attributed to faulty apparatus as long as
a possibility of improvement remains. Consequently in the work herein described no attempt has been made to refine the individual measurements but rather to set a certain standard of accuracy that all measurements must satisfy and to eliminate from the apparatus every possible source of gross error.

Form of Apparatus.

The wire to be tested must of course be enclosed in a box so that it may be raised to a high temperature. However it must not be permitted to come in contact with any portion of this box but must be freely suspended. The method employed to secure free suspension is shown in Fig. 1. A light flexible cord passes from the weights (W) over the pulley (P) and is joined to the wire to be tested by means of the glass coupling (a) which serves as an insulator, as does also the adjustable support (b) at the other end of the wire.
Fig. 1.
Current is lead to the wire at (d) and (d) by means of the mercury cups (c). Three thermo-elements (th) wrapped around the wire are for temperature measurement. These are of very fine flexible wire. It will be observed that except for the thermo-elements the wire is freely suspended and is subjected to no mechanical forces other than its own weight and that of the weights (W). In order that the heat generated by the current in the wire may be retained and to furnish a means of heating the wire from outside a long narrow box as shown in Fig. 2 is placed about the wire. The base (e), bottom piece (f), and back (l), the latter two being covered with asbestos are securely fastened together. The asbestos covered front (h) which has two windows of mica (m) for observing the wire and the glass cover (i) are held by clamps. The glass tubes (k) are large enough to give a large clearance to the wire (g) but small enough to prevent convection or other air currents.
Fig. 2.
The space (j) between the tubes and the box is filled with glass wool. Zigzagging back and forth across the bottom piece (f) is placed a heating wire of german silver.

It is of the greatest importance that the force of the weights (W) be transmitted to the wire with no loss. A wheel, the means usually employed, was not considered at all. Instead a pulley of the form shown in Fig. 3 was constructed. An aluminum disc (D) was turned out and a small hole (n) drilled exactly in its center while it was still in the lathe. By means of adjustable brass pieces (p) two sharp pointed screws (s) are brought into such a position that the line between the two points as determined by try square and sighting through the hole passes perpendicularly through the center of the disc. Part of the pulley is cut away but a counter weight is added as indicated. It has been found by trial that the error due to the pulley is too small to be detected.
Fig. 3.
The stretching of the wire is measured by means of two micrometer microscopes attached to the engine bed. The additional weight \( W_n \) is added and removed quickly and without shock by an apparatus operated by the foot.

**Measurement of Temperature.**

Attention has already been called to the fact that some of the earlier investigators found that current caused lengthening. The work of Basso, Exner, Blondlot, and Righi (Wiedemann's Elektricitat) although not conclusive seems to indicate that the only change in length due to current can be accounted for by the temperature. It would seem as if change of length should be an accurate method of measuring temperature, but since the evidence is not conclusive and this method has not resulted in anything like satisfactory results in the case of Miss Noyes it was decided to employ a means of measuring temperature independent of any temperature effect in the wire itself.
The temperature is determined at three points on the wire by means of copper-constantin thermo-elements of #36 silk covered wire. These are connected to a Siemens and Halske galvanometer through a three way switch. A thermos bottle has been found a most reliable means of keeping the cold junctions at zero. The temperature calibration is made directly in terms of galvanometer deflections as indicated in Fig. 4.

Since heat is generated in every part of a current carrying wire there is conduction of heat from the inside of the wire outwards. Consequently there is an increase of temperature in the center resulting in a number of effects each of which has its effect upon the current distribution and in turn upon the temperature distribution. Since the thermo-elements read surface temperature only, it is necessary when the wire is carrying current to correct this reading in order to find the average temperature throughout the cross section of the wire.
Calibration of Thermoelements.

**Fig. 4.**

Galvanometer Deflection vs. Temperature.
A mathematical analysis would give a formula for average temperature in terms of surface temperature, current, and a number of constants varying with the size and material of the wire. The use of such a formula is open to the objection that the accuracy of the results depends on whether or not the thermo-elements read the true surface temperature of the wire. It was decided to get around this difficulty by making the assumption that constancy of length indicates constancy of average temperature. Then correction curves can be made as follows. The wire is heated externally to a certain temperature as is indicated by the galvanometer (thermo-element) readings. The length is observed and maintained constant while greater and greater current is passed through the wire, the current through the heating coil being of course decreased at the same time. In this way, as the current increases, the same average temperature is found to be represented
by decreasing galvanometer deflections. The series of curves is shown in Fig. 5, in which the vertical lines are only to facilitate the reading of the corrections. Observations were taken at four temperatures (average), 41°C, 72°C, 101°C, and 137°C, approximately. Each series of plotted points indicates observed combinations of current and thermo-element readings that accompanied the same length. For instance the same length (same average temperature) was caused by a thermo-element reading of 137°C and zero current, by a thermo-element reading of 128°C and 8.7 amperes, and by a thermo-element reading of 124°C and 13.8 amperes. It will be noticed that if the thermo-elements do not read the exact surface temperature, this is taken care of automatically by this method.

When no current is passing the wire is of uniform temperature throughout and the thermo-elements give the true average temperature. But as
Fig. 5.
more and more current is passed the difference between the average temperature and the thermo-element reading increases. For any combination of surface temperature and current there exists a definite average temperature. For instance if we have a thermo-element reading of 115°C and a current of 8 amperes we find this point to be on the 120°C curve. The correction will be 5°C which is to be added to the observed surface temperature to find the average temperature.

The use of thermo-elements has one decided advantage and that is that by slipping the elements to different parts of the wire the distribution of temperature can be found. As it took the author a number of days to secure uniformity of temperature it is believed that herein lies a fertile source of error in previous work in which the temperature was measured by change of length or resistance. In these instances the precautions taken to secure uniformity of temperature were of a sort found by the present writer to be inadequate.
Measurements.

The measurements that enter into the determination of Young's modulus are made as follows:

Length of wire. While the observing microscopes are still in position the wire and heating box are removed and a standard meter substituted. The distance between the cross hairs is the length of the wire.

Diameter of wire. Using one of the microscopes and taking observations both from the side and from the top a series of readings are taken and the average diameter computed.

Mass of weights \((W, \text{ and } W_w)\). Using the Iowa State standard kilogram and other standard weights the mass of the stretching weights is found.

Value of "\(g\)". The value of "\(g\)" is used as computed for the latitude and elevation of Iowa City.

Value of divisions of micrometer head. The number of revolutions per mm. is determined for several different divisions of the standard meter and the number of mm. per revolution computed.
Measurement of stretch. A scratch upon the copper wire is always brought by means of the dividing engine screw between the cross hairs of one microscope. The stretch of the wire is observed by the other telescope.

Calibration of thermo-elements. This is done with an accurate thermometer.

Measurement of temperature. As described above.
Method of Taking Observations.

Observations have been taken during the past winter upon two copper wires. Each was first heated to a high temperature and straightened by the weight (W). This weight was always kept upon the wire. The range of temperature was about 20°C. to 140°C. The usual plan was to start in the morning with an observation at room temperature and gradually heat the wire by 20° to 30° steps taking observations as often as possible (half hour to hour). It was found that at least twenty minutes was required for the wire and enclosing box to reach a state of temperature equilibrium. The wire would then be cooled by similar steps and again heated if time permitted. This method was of course subject to great variations, the wire being at times heated at once to high temperatures. At other times only extreme temperature conditions were observed etc. etc.
For any given temperature the observations were as follows. The three thermo-element readings are taken. The right observing point is then brought between the cross hairs of the telescope by means of the engine screw. The cross hairs of the left microscope are brought to the left observing point and the reading of the micrometer head recorded. The additional weight \(W_n\) is added by means of the foot lever and the right observing point brought into place again. As quickly as possible the left cross hairs are again set, the difference in the settings of the left micrometer screw giving the amount of stretch. About ten such readings are taken and the thermo-elements read again.

**Sources of Error and Accuracy of Work.**

When a wire is stretched horizontally its weight causes it to hang as a catenary. Consequently a part of the apparent lengthening caused by the addition of a weight is due to the straightening of the wire. In order to
determined the influence of this factor, the value of \( c \) in the formula for the catenary \( y + c = \sqrt{\frac{c^2}{s^2} + s^2} \) was computed in terms of length of wire. The vertical motion of the two observing points and the center was computed and found to correspond to the observed motion. From these values was found the error due to straightening of the wire, which error amounted to about 1/100 of the smallest reading of the micrometer screw.

About 3,000 single observations have been made but the chief use of the greater part of these has been to indicate in what direction to seek for improvement in the apparatus and method. At the time of writing the apparatus possesses the following advantages. The wire is free from contact with any body which might affect its position or apparent length. The wire is mounted in a box arranged to secure uniformity of temperature over the portion under observation. The force of the weights is applied to the wire itself without loss or gain. Although these conditions are essential to satisfactory work the results of previous investigators would indicate that they have not been secured.
Results.

On the following sheets are found data and curves for four series of readings for Wire #2.

The meaning of the symbols used at the head of the columns of data on the following sheets is:

- **Obs. no.** Observation number
- **Time** Time of observation
- **Temp.** Average temperature of wire
- **T (obs)** Temp. of surface as indicated by thermo-elements
- **T (cor)** Correction applied to T (obs) in the case of current heating in order to get "Temp."
  \[ \text{Temp.} = T \text{ (obs)} + T \text{ (cor)} \]
- **I** Current in the wire (amperes)
- **Stretch** Stretch in terms of revolutions of micrometer screw
- **Y. M.** Young's modulus, (the numbers given are to be multiplied by \(10^{11}\) to give the modulus in dynes per cm.\(^2\)
Data Concerning the Wire.

Length of wire (observed portion) .................. 50.7 cm.
Diameter of wire ........................................ 0.61 mm.
Mass of \( W_1 \) ............................................. 2109. g.
Mass of \( W_2 \) ............................................. 2252. g.
Value of "g" .............................................. 980.2
Stretching force due to \( W_1 \) ..................... \( 2067 \times 10^3 \) dynes.
Stretching force due to \( W_2 \) ..................... \( 2207 \times 10^3 \) dynes.

Value of divisions of micrometer head

- \( 1 \text{ mm.} = 21.42 \text{ revs.} \)
- \( 1 \text{ rev.} = .047 \text{ mm.} \)
- \( 1/50 \text{ rev.} = .00093 \text{ mm.} \) (smallest reading)

Amount by which wire straightens when \( W_2 \) is added, or
the vertical motion of the center relative to the
observing points ....................................... .03 mm.

Formula used ........................................
\[ M = \frac{46.8 \times 10^{11}}{\text{Revs. (stretch)}} \]
(no account is taken of change
of length with temperature)
Wire #2, Series #4.

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External heating.

March 6 & 7, 1912.
External heating

Wire remained over night at 135°C. (Readings 2-3)
## Wire #2, Series #5

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*External heating.*

*March 9, 1912.*
Wire #2, Series #5.
Wire #2, Series #6.

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Internally heated.

March 12, 1912.
Young's modulus

Temperature

$10^6$ dynes per sq cm

Internal heating

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<td>2</td>
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</table>

Internally heated.

March 13, 1912.
Internal heating

- Increasing temperature
- Decreasing “
- Increasing “
- Decreasing “

Wire #2, Series #7.
Wire #2, Series #9.

Observations taken with internal heating, both A.C. and D.C., and with external heating. The length was kept as constant as possible.

<table>
<thead>
<tr>
<th>Observation number</th>
<th>Method of heating</th>
<th>Reading of screw indicating length</th>
<th>Stretch (revs. of screw)</th>
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<tbody>
<tr>
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<td>32.09</td>
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<td>12.8 D.C.</td>
<td>32.24</td>
<td>4.30</td>
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<td>6</td>
<td>External (D.C.)</td>
<td>32.23</td>
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<td>7</td>
<td>External (A.C.)</td>
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<td>8</td>
<td>12.2 D.C.</td>
<td>32.12</td>
<td>4.30</td>
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</table>

The greatest variation in length is 0.15 rev. of the micrometer head or about .008 mm. This corresponds to a temperature variation of less than one degree Centigrade.

The variation in stretch is not more than the experimental error.
Discussion of Results.

From the curves and data shown on previous pages and other results that are not shown we can at once reach a number of important conclusions regarding the particular wires employed.

1. Young's modulus decreases about 10% when the wire is heated either externally or internally, from 20°C. to 140°C.

2. The decrease in Young's modulus is not a linear function of temperature.

3. The indications are that the permanent changes in Young's modulus due to repeated heating and cooling are relatively small and that the nature of the temporary changes is not much altered by any permanent changes there may be.

4. Passing from D.C. to A.C. internal heating and to external heating and regarding constancy of length as an indication of constancy of mean temperature, no change in Young's modulus can be detected.
(5) There are indications however of a difference due to current when the wire has been allowed to cool in the meantime. But it is believed that the use of a more steady current and slight changes in the apparatus may show this to be caused by experimental error. It will be so regarded until another conclusion is inevitable.

**Future Work.**

Only enough curves and observations have been referred to and shown to indicate that already some very consistent and conclusive results have been obtained. The way is now open for a large amount of work upon different materials. Preparations are being made for the use of steady direct current from storage cells so that the work can be continued at once.
Although the use of thermo-elements has been essential to the securing of uniform temperature along the wire, it is expected that the measurement of temperature in terms of lengthening may prove to possess some advantage.

It is expected that the presence of current will prove to have no measurable effect upon Young's modulus except through the heating effect, but it is still an open question as to whether or not a wire heated by a current will have a different elastic history than one heated otherwise. The study of various kinds of wire and the use of much higher temperatures will undoubtedly prove of great value.

While this is being done the pure temperature effect will of course be found with considerable accuracy. These results of these control experiments alone will be worth the labor. Regarding the temperature effect but little is known. Some investigators have measured Young's modulus at
two or three temperatures. Only a few have taken observations at frequent intervals over considerable temperature ranges, and their work does not agree. Consequently the continuation of this investigation will not only lead to a knowledge of the effect of current upon the elasticity of wires but also the effect of temperature and of history.

In conclusion I wish to express my great appreciation of the assistance of Professor Stewart who not only suggested the problem but has kept in constant touch with the work and aided with suggestion and encouragement.


State University of Iowa, Iowa City, Iowa. May, 1912.
H. L. Dodge.