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Note on the Vibration of Ferromagnetic Wires placed in a Varying Magnetizing Field.

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1. It is well known that ferromagnetic bodies emit an audible sound at the moment of making and breaking the magnetizing current. Page[1] first heard the sound in the magnet, when an electric current passed through a copper spiral placed between the poles of a horse-shoe magnet. The sound was more intense at the break than at the make. A Similar phenomenon was also observed by Delezenne[2]. Marrian[3] placed an iron or steel wire in a coil, and by making and breaking the magnetizing current, he heard a sound due to the longitudinal fundamental vibration of the wire. Matteucci[4] examined the effect of tension and found that the pitch of the sound was independent of the tension, but that the intensity was decidedly increased. The investigation with iron bars of different lengths led

1) Page, Pogg. Ann. **43**, 411, 1838; Wiedemann's Electricität III, 838.
2) Delezenne, Bibl. univ. ser. nouv. **16**, 406, 1838.
3) Marrian, Phil. Mag. **25**, 382, 1844.
4) Matteucci, Archives **5**, 389, 1845.

Wertheim[1] to the conclusion that each bar vibrated in its fundamental mode. By passing an intermittent current through the magnetizing coil, he heard a continuous sound, the pitch of which was the same as that of the make or break of the current. The thickness of the bar had no effect on the pitch of the sound. Nonmagnetic bodies gave no sound under similar conditions. He then concluded that the vibration of the wire was produced by the magnetic change of length. Beatson[2] noticed a sound produced in a stretched iron or steel wire carrying an intermittent current. De la Rive[3] tried, not only the bars of iron and steel, but also those of lead, zinc, bismuth, tin, antimony, platinum, gold and silver. He placed these bars between the poles of an electromagnet and passed an intermittent current through them. They all sounded, the ferromagnetic metals producing sound only with the intermittent current through them, although there was no magnetizing field acting. The experiments with fine powders of several metals and coaks gave similar result. He ascribed the phenomenon to some transpositions of molecules. Ferguson[4] and Ader[5] noticed similar phenomenon with intermittent as well as alternate currents. Trowbridge[6] found that nickel and cobalt also produced sound under similar conditions. In studying the effect of tension and compression on the intensity of sound produced in iron and nickel bars, Bachmetjew[7] found that the effect was parallel to that of the tension on the magnetic change of length. He thus concluded that the intensity of the sound is a function of the change of length by magnetization.

1) Wertheim, Pogg. Ann. **77**, 43, 1848.
2) Beatson, Electr. Mag. April 1846; Arch. de Genève **2**, 113, 1846.
3) de la Rive, Phil. Trans. **1**, 39, 1847; Pogg. Ann. **76**, 270; Arch. des Sc. phys. et nat. **25**, 311, 1866; Pogg. Ann. **128**, 452; Ann. de chim. et de phys. [4] **8**, 305, 1866.
4) Ferguson, Pro. Roy. Soc., Edinb., March 6, 1878; Beibl. **3**, 205.
5) Ader, Compt. rend. **88**, 641, 1879; Beibl. **3**, 642.
6) Trowbridge, Beibl. **3**, 289, 1879; Proc. Amer. Acad. **11**, Dec. 114, 1878.
7) Bachmetjew, Exner's Rep. **26**, 137, 1890; Beibl. 14, 537.

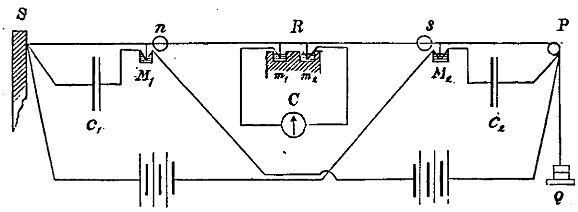
2. A short consideration of these results leads us to distinguish three kinds of the sound. The first is the combined effect of the magnetic force and the electric current. The sounds noticed by Page, Delezenne and de la Rive belong to this category; they do not depend upon the magnetic property of the substance, but on the mechanical action produced by the magnetic force and current.

The second kind of sounds accompanies the magnetization or demagnetization of a magnetic substance at the make or break of a magnetizing current. The sounds noticed by Marrian and others belong to this category. The cause of the sound is probably the change of length by magnetization. When a magnetic substance is suddenly magnetized or demagnetized, it elongates or contracts and attains its final length, after several oscillatory changes in length have occurred in quick succession. This oscillation will produce a clinging note at the moment of magnetization or demagnetization. This view is favoured by the experiments of Marrian and Wertheim. But Matteucci found that the tension does not affect the pitch of the sound; if his result were true, the vibration would be of more complex nature.

The third kind of sounds is one accompanying magnetization by an intermittent or alternate current of a definite frequency, or one produced when the above mentioned current is passed directly through the substance. The sound is probably produced by the continuous series of vibration above referred to. The experiments of Beatson and others will agree with this view.

De la Rive and Wiedemann ascribe the cause of the phenomenon to the molecular effect, but Wertheim and Bachmetjew to the magnetic change of length. We also consider it highly probable that the change of length is the cause producing the sound belonging to the second and third kinds. The present experiment was undertaken to get a clearer insight into the nature of the phenomenon.

3. In all previous experiments, the range of the frequency of an intermittent or alternate current was very limited ; but in our case, a string alternator[1] was introduced for continuously varying the period of the current. The arrangement is shown in the annexed figure. A copper wire is horizontally stretched ; one of the ends is fixed to a support S, while the other passing over the pulley P is attached to a weight Q. The wire is electrically insulated at the centre R, so that the current through the two mercury cups m_1 and m_2 flows in the circuit C. The battery currents pass through the two mercury contacts M_1 and M_2. The vibration of the string is maintained constantly oscillating by the electromagnet n and s. If the string is set in vibration with a single node at R, an alternate current is produced in the circuit C ; if only one set of batteries is used, an intermittent current is produced in the same circuit. The frequency of alternation or of interruption can easily be varied by the change of length and of tension of the wire. c_1 and c_2 are two condensers with a suitable capacity to diminish the sparks at the mercury contacts M_1 and M_2.



For the study of the vibration of a ferromagnetic wire under a varying field, we used Professor Nagaoka's apparatus for the measurement of the minute change of length. In the present experiment, the glass fibre in the slit of the collimator was removed and the fine slit illuminated by a gas flame was used instead. The image of the slit, after reflection by the revolving mirror and refraction through a

1) K. Honda and S. Shimizu, Amer. Jour. Sc. **10**, 64, 1900 ; Phy. Zeitsch. 2 Jahrgang, **25**, 371, 1901.

converging lens, was formed in the field of a micrometer ocular. If the wire makes a rapid longitudinal vibration, its amplitude can be measured by observing the broadening of the image of the slit.

The wire to be tested was 21 cm long and 1.50 mm thick. The magnetizing coil was 30 cm long and wound in 4 layers on a wooden frame and gave a field of 19.82 C.G.S. units due to a current of one ampere. The coefficient of self-induction of the whole circuit was 5.2×10^6 cm and its resistance 12.9 Ω, so that the time of relaxation was 4.0×10^{-4} seconds.

4. The results of experiments may be summarised as follows :—

(a) Wires of nonmagnetic metals give no sound by an intermittent or alternate field of any frequency up to 200 per second.

(b) A ferromagnetic wire emits an audible sound in an intermittent or alternate field.

(c) The pitch of the sound is always the same as that of the make or break in an intermittent or alternate current.

(d) The amplitude of vibration is in general far greater than the change in length produced by a constant field of such strength that it is equal to the maximum value of the intermittent or alternate field.

The pitch of the sound was determined by tuning a monochord to the period of the sound and counting the number of beats. From the results above mentioned, we may safely conclude that the sound produced in the ferromagnetics is due to the magnetic change in length of the wire. One make or break of the current forces the wire to accomplish a vibration, and a succession of such series constitutes a sound, the pitch of which is the same as that of the make and break. If this view be true, the pitch of the sound due to an alternate current must be double that of the sound due to an intermittent current for the same number of vibrations of the string alternator, because the magnetic change of length is independent of the direction of the field. By an actual experiment analogous to that of Lissajous, we found this inference to be verified. The above results also show that the magnetic change of length occurs so quickly as to follow rapid changes of magnetization of as much as 150 reversals per second.

If the frequency be kept constant, the relation between the amplitude of vibration and the maximum field during one complete period of vibration is similar to the relation of the change of length to a steady field. The maximum field used in most of our experiments was 30.7 C.G.S. units.

It is also to be observed that if an intermittent or alternate current is passed through a spiral of nonmagnetic metal, an audible sound is produced. This is perhaps due to the periodic attraction of the currents flowing through the spiral in the same direction, and is of a quite different nature from the sound above referred to.

5. Gradually varying the frequency of the intermittent or alternate current, while the range of the field was kept constant, we observed the singular phenomenon that the amplitude of vibration passed through several maxima and minima. Two marked maxima and minima were observed in the case of nickel wire. The maxima occurred at the frequencies of 80 and 150 per second, while the minima at the frequencies of 68 and 140 per second. The phenomenon which was chiefly due to the longitudinal vibration of the wire, was, to a certain extent, modified by the resonance of the system, consisting of a reflecting mirror and two springs attached to it,

to the periodic vibration of the wire due to the magnetic change of length. The positions of the maxima and minima were not, however, materially changed by the length of the wire, or the tension of the springs. In the case of iron, the magnetic change of length for the same field strength was small, so that the phenomenon was not very marked.

To study the phenomenon specially, we used another arrangement; the apparatus was the same as that described in the preceding paper, used for the measurement of the magnetic change of length under constant tension. The wire to be tested was about 60 cm long and 0.4 mm thick; to the extremities of the wire, two copper wires of nearly the same thickness were soldered. It was hung vertically in the axial line of a magnetizing coil 80 cm long so as to lie nearly in a uniform field, and to its lower end was attached a weight. Near the lower end of the copper wire, a thin rotating cylinder carrying a reflecting mirror was placed horizontally and came in contact with a suitable pressure to the vertical wire. The working of the arrangement was the same as in the preceding experiment.

The magnetizing coil was wound in 4 layers and gave a field of 26.0 C.G.S. units due to a current of one ampere. The coefficient of self-induction of the whole circuit was 1.66×10^7 cm and its resistance 18.2 Ω, so that the time of relaxation was 9.1×10^{-4} seconds.

With the above arrangement, we found also two marked maxima in the amplitude of vibration for iron as well as for nickel. The amplitude of vibration is plotted against the frequency of the current in Figs. 1 and 2. In both cases, the maximum field during one complete period of vibration is 28.5 C.G.S. units, and the weight attached to the lower end of the wire is reduced to the weight per square millimeter.

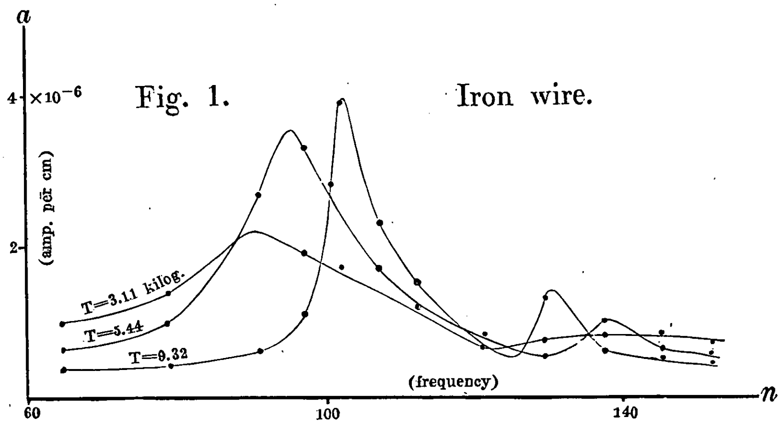


Fig. 1. Iron wire.

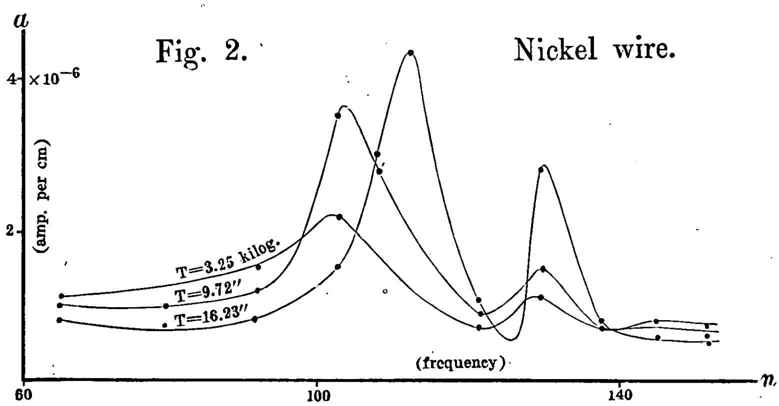


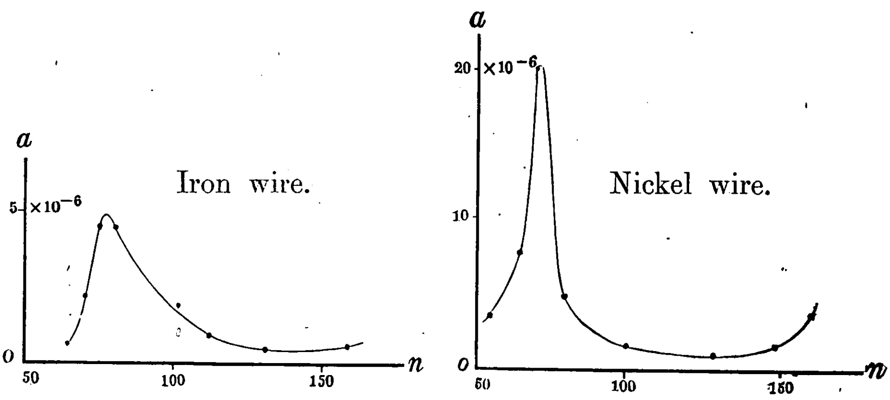
Fig. 2. Nickel wire.

As will be seen from the figures, the maximum amplitude of vibration and the frequency corresponding to the maximum increase with weight. By altering the length of the ferromagnetic wire, the positions of the maxima and minima are but slightly affected.

These positions of the maxima and minima do not coincide with those in the former case; the first maximum occurs in a higher frequency and the second in a lower one, the difference amounting in each case to about 20. The first maximum is also of a frequency higher by at least 2.5 times than that calculated on the consideration that the phenomenon is due simply to the elastic vibration of the wire.

Instead of attaching a weight to the free end of the wire, the same end was stretched by means of a spiral spring fixed to the stand. Varying the frequency of the intermittent or alternate current, the maxima and minima of the amplitude of vibration were also observed, as shown in Fig. 3. In this case, the first maximum occurred at a frequency of about 75 per second for iron as well as for nickel, and the second at a frequency higher than 160 per second for these two metals. These positions of maxima and minima were almost independent of the tension and of the length of the spring.

Fig. 3.



Whether these complicated phenomena are capable of being explained simply by the elastic vibration and the magnetic change of length without taking account of the time-lag, or whether they prove the existence of this effect, requires further experimental and theoretical considerations.

Our best thanks are due to Professor Nagaoka and also to Professor Tanakadate for their kind guidance in carrying out the present experiment.