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XXIV. *On some Physical Points connected with the Telephone.*

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THE introduction of the speaking telephone, by Alexander Graham Bell, has supplied physicists with an instrument of research as well as with an instrument of practical utility. It is an apparatus which, for the examination of certain kinds of currents of electricity, is the most delicate that has yet been invented. Indeed it has rendered evident the presence of currents whose existence, though suspected, have hitherto eluded the grasp of the electrician; in fact its very delicacy has proved the greatest obstacle to its general adoption.

I. *The Telephone as a Source of Electricity.*

Faraday showed that, when a closed conductor is moved across the lines of force in a magnetic field, a current of electricity is generated within that conductor whose strength is dependent upon the velocity of motion of the conductor and upon the intensity of the magnetic field. It is, in fact, proportional to the number of lines of force cut through per unit of time. And also, when lines of force are projected through a closed conductor, a current of electricity is generated in that conductor, whose strength depends upon the magnetic intensity of those lines of force, or upon their number per unit area. The direction of the current in each case is found by Lenz's law, viz. that the current produced tends to resist the motion producing it. The new principle that has been developed by Professor Graham Bell is that the form and duration of that current is dependent upon the rate and duration of the motion of the moving body or of those lines of force.

Let NS , fig. 1, be a permanent magnet, and ab a fixed, closed, conducting ring of copper around one pole of that magnet. Let c be a movable iron armature. Now, if we regard any two lines of force 1 radiating from the pole N , and nearly cutting the ring ab , then, as we make c approach or recede

* Read January 19, 1878.

from *N*, those lines of magnetic force will change their direction, taking up position 2; and with each change of direction they will cut the ring *a b*, and currents of electricity in different directions will circulate through *a b* according to the direction of motion of the lines of force; and the rate of increase and decrease of magnetic intensity (or of the increment and decrement of the current) will vary directly with the rate of motion of the armature *c* to or from the pole *N*. Thus, if *c* be a disk of iron vibrating under the influence of sound, the excursions to and fro of any point of the disk, though very small (in fact they are so small that they can scarcely be detected by the most delicate means—so small that they have led Graham Bell to imagine that the vibrations are molecular), are nevertheless sufficient to produce that motion of the lines of force which results in currents. It is, however, a fundamental principle in acoustics, that wherever there is sound there is always vibration. Sound and vibration are concomitant and inseparable phenomena. The air cannot produce sound unless it is thrown into vibration; and the air itself cannot be thrown into vibration unless the mass of matter in contact with it vibrates also. The amplitudes of vibration of the particles of the air themselves have never been measured, though the length of a sound-wave (a very different quantity) is accurately known. Lord Rayleigh has shown that an amplitude of only $\frac{1}{10000000}$ of a centimetre is sufficient to produce sonorous vibrations. But though the amplitude of the vibrations be so small they are rapid. Now this rate of motion is sufficient to bend in the same ratio the lines of force cutting *a b*, and thereby to produce currents of electricity in the ring *a b* whose number depends on the number of vibrations, and whose form and intensity depend on the rate and amplitude of motion of the disk *c*. These currents are alternate, and so rapid that no known instrument but the telephone indicates them; but they are readily shown by a Thomson's reflecting galvanometer when the disk is gently and slowly pressed in by the finger,—in one direction when the disk is pressed in, in the other direction when the disk is allowed to fly back.

I have failed hitherto to make even an approximate measurement of their minuteness. We have no known standard to compare them with: we can only trust to the ear; and that

instrument is not only deceptive but variable. They are certainly less than $\frac{1}{1000000}$ of an ordinary working current. Mr. R. S. Brough, of the Indian Government Telegraph Department, has calculated that the strongest current with which a telephone is at any moment worked does not exceed $\frac{1}{1000000000}$ of the C. G. S. unit, or *weber*; and Professor Pierce, of Boston, found that similar effects are produced with an electromotive force of less than $\frac{1}{2000000}$ of a volt or Daniell's cell. Thus we have a source of electricity competent to produce currents of microscopic strength, which vary in form, duration, and intensity with the motion of the body producing them.

II. *The Telephone as a Detector.*

Fig. 2.

Let n s, fig. 2, be a core of soft iron surrounded by a closed conductor $a'b'$, through which currents flow. Now this core will become magnetized with an intensity dependent solely upon the intensity of the current; and the intensity of magnetism at any moment will be a function of the intensity of the current at that moment; so that if the current increase and decrease with a given ratio and at a given rate, the intensity of magnetism will increase and decrease with the same ratio and at the same rate. The disk c' is elastic, but it is rigidly fixed at its axis; it being of iron, it is attracted at any moment with a force dependent upon the intensity of the magnetism of the core n s, and being elastic, it recovers, or tends to recover, its normal position whenever this intensity of magnetism ceases or diminishes. Thus, if the magnetic intensity varies, the force of attraction varies, and the rate of motion of the disk varies in the same way. Hence the disk will record exactly the variations of the currents; and as the currents are the result of the variations of the vibrations of another disk, the one disk c' simply repeats exactly the vibrations of the other disk: thus sounds are reproduced.

Though in the earlier instruments the coil surrounded a pole-piece of soft iron, this pole-piece has since been discarded, and the coil surrounds the pole of the magnet itself. The efficacy of the instrument has been in no way impaired by this change; and it has the additional advantage of being perfectly

reversible, the same instrument being used for speaking and for hearing.

III. *Working the Telephone.*

There is a remarkable difference in the power of different voices to work the telephone. Shouting is of no use. The intonation must be clear and the articulation distinct, and the style of conversation approach more the sing-song. I have heard Mr. Willmot, one of the electricians of the Post Office, through resistances that have drowned all other voices. The vowel sounds always come out the best; the palatal sounds *c, g, j, k* and *q*, the worst; in fact, the latter sounds are frequently lost. The ear also requires a certain education; and the power of hearing varies surprisingly with the different ears and with different people. Singing always comes through with remarkable distinctness; and the sounds of a wind-instrument—the cornet or the bugle—are reproduced with startling force. A bugle sounded in London was heard distinctly over the large Corn Exchange of Basingstoke by a thousand people. This arises from the regularity as well as increased amplitude of the sonorous vibrations, and consequently from the regularity, uniformity, and increased strength of the currents of electricity.

IV. *Improvements.*

Every one who has the means at his disposal has been endeavouring to increase the power of this instrument. I should be sorry to enumerate the number of experiments I have tried, but all with vexatious, disappointing, and dispiriting failure.

One of the earliest efforts was made by Mr. Willmot, who hoped by increasing the number of diaphragms, coils, and magnets acted upon simultaneously, and joining up all those coils in series, to obtain a resultant effect that would magnify the out-going currents; but the result showed that, while the apparatus acted all right, the effect of displacement of each diaphragm decreased with their number, and the ultimate effect was the same as with one diaphragm. Mr. Willmot's instrument, which was made early in October last, is on the table; M. Trouvé, in Paris, seems to have been working on the same idea.

Increasing or varying the size, form, and strength of the magnet has produced little or no apparent improvement; for the resultant effect in all cases remained apparently the same.

The greatest effect is produced with a compound horseshoe magnet, which is indeed one of the earliest forms brought out by Mr. Bell. Here we have two coils, utilizing the maximum number of lines of force; and the effects produced are certainly the finest I have yet experienced. At Southampton, on the 14th inst., in a small office, Mr. Willmot's voice (he was in London) was heard distinctly by the seven or eight persons who were in the room at the time. Though I have made one with the largest and most powerful magnet I could obtain, the result has been as disappointing as in the previous cases. The telephone has certainly been brought to this country by Mr. Bell in almost its perfect theoretical form; he is still labouring to improve it; and I am sure we all wish him success.

V. Applications.

However small and however sudden the currents may be, the telephone records them with great accuracy; no known form of galvanometer or galvanoscope will do so.

It is admirably adapted for showing the currents of induction set up in contiguous coils or contiguous spirals. If reversals or intermittent currents be sent through one spiral while the other be gradually removed away, the rapidly diminishing effect of increased distance is very evident; indeed all the phenomena of magneto-electric induction are strikingly shown by its means. It is also admirably adapted as a detector in the bridge of a Wheatstone's balance to test short lengths of wire, and it will probably enable us to obtain a closer approximation to equality than we have yet secured; it also enables us to adjust condensers with great accuracy.

M. Niaudet, of Paris, has shown how it can be utilized to detect the presence of extremely feeble currents from doubtful sources of electricity. If currents from the supposed source be rapidly sent through one wire of a double-wound coil, and a telephone be fixed on the other running parallel to it, then the telephone would give evidence of their presence, which would be indiscernible on any other instrument.

It is admirably adapted also for testing leaky insulators and supports.

VI. *Inferences and Results.*

The telephone explodes the notion that iron takes time to magnetize and time to demagnetize. If time were occupied in magnetizing, notes would be changed or lost ; but they are not altered. The notion of time is due to the action of induction in coils producing *reaction* and *extra currents*. This is proved by the insertion of an electro-magnet or of coils of wire in a telephonic circuit. While it is possible to speak through a cable 100 miles long laid out straight in the sea, it is impossible to speak through 20 miles when coiled in a tank.

Its delicacy has detected the presence of currents in wires contiguous to wires conveying currents, which have always been suspected, but have been evident only on wires running side by side for several miles (say two hundred) on poles or in well insulated cables. In fact, the most delicate apparatus has hitherto failed to detect the presence of these currents by induction in short underground wires ; but the telephone responds to these currents when the wires run parallel for only a few feet. Thus, between one floor and another floor, at the General Post Office, it has been impossible to converse by means of the telephone through a wire, owing to the presence of these currents of induction from the innumerable working wires contiguous to it, and through some of the underground pipes of the streets of London sounds are inaudible when the wires are working. In fact, two small-sized gutta-percha wires, *one foot long*, were lashed side by side by Mr. Marson ; and when battery currents were sent through one, induction currents were distinctly heard on a telephone fixed on the other. Indeed this induction between wire and wire, has proved the most serious obstacle to the practical introduction of the instrument. But it is not altogether irremediable on underground wires ; it can be surmounted in three ways :—

1. By increasing the intensity of the transmitted currents so as to overpower the currents of induction, and by reducing the sensitiveness of the receiving apparatus so as to make the instrument insensible to currents of induction though responsive to telephonic currents.

2. By screening the wire from the influence of induction.
3. By neutralizing the effects of induction.
1. Mr. Edison in America has partially succeeded in effecting the first cure ; but his results, though promising, have not yet reached a practical point.
2. I have overcome the second difficulty in a way that will now be described.

Let 1, fig. 3, be a wire used for telephonic purposes, and 2

Fig. 3

be an ordinary telegraphic wire contiguous to it. Let us regard 1 and 2 as symmetrical and contiguous particles of the two wires. If a current flow through 2 it will affect 1 inductively both statically and magnetically. Let us regard the static effect first. If the current flow away from us, then we may consider the particle 2 as charged *positively* ; lines of electric force will radiate all around it, and that line which passes through 1 will inductively charge that particle *negatively*. This influence being felt all along the wire, a current in the reverse direction to that in 2 will flow through 1. The reverse would occur if we assumed the primary current to flow in the other direction. Hence, an induced current will flow through 1, whenever the current in 2 commences and whenever it ceases. Now, if we place between 1 and 2 a screen of metal, or other conducting matter, in connexion with the earth, then

the line of electric force, instead of passing through 1, will terminate at the screen. Hence, if we surround the wire 2 with a covering or sheath of metal, or if we submerge it in water, all effects of static induction will cease between 1 and 2. In water they are not entirely eliminated, for water is a very poor conductor; but they are so reduced by its influence, as my experiments between Manchester and Liverpool and between Dublin and Holyhead have shown, that, if the water or wet serving had been a perfect conductor, they would have been removed as far as regards static induction.

But we have to regard magnetic induction as well. Besides establishing a field of electric force around 2, a current flowing through that wire establishes a magnetic field around it, whose lines of force are circles, and whose directions are at right angles to the lines of electric force. Let us regard that line of force cutting 1. Each time a current commences, and each time it ceases, in wire 2, a line of magnetic force cuts wire 1, and produces in that wire a current of induction in the same direction as that produced by static induction. Now, if we make the screen of iron, those lines of force terminate in the iron and wire 1 is freed. Hence, if we sheath the wire 1 with iron, it is not only freed from the effects of static induction by being surrounded by a conductor in contact with the earth, but it is shielded from the effects of magnetic induction by its sheath of iron. Hence both effects of induction are entirely removed.

3. They can be neutralized by means of a return wire, using this return wire instead of the earth. If 1 and 2, fig. 4, be

Fig. 4.

two wires running side by side, then the current set up by induction from neighbouring wires in one wire is neutralized by the currents set up in the other side.

But this assumes either that the disturbing wires are at an infinite distance from 1 and 2, or that 1 and 2 are infinitely near each other. All attempts to use return wires on existing poles, in cables, or in underground wires have utterly failed to do away with inductive disturbance; but Mr. Bell has had a

single gutta-percha wire carrying two conductors made which very nearly fulfils the conditions and gives excellent results.

The extreme delicacy of the instrument has introduced a disturbance from another cause, viz. leakage. Wires on poles are supported by glass, porcelain, and earthenware insulators; but the best support that was ever devised is but a poor insulator in wet weather. Currents escape over their surface from the wire they support; and these leakage currents find their way into telephonic circuits. Hence a telephone circuit which may work well in dry fine weather will prove absolutely unworkable in wet weather.

Another source of trouble arises from what are technically called "bad earths." It is almost impossible to make a perfect connexion with the earth. There is always some resistance at that point; so that if two wires terminate on the same earth-plate, the one being a working circuit and the other a telephone-circuit, some currents from the former are sure to pass through the latter and disturb the telephone. A return wire perfectly cures this evil.

There are other disturbing elements that are peculiar. Earth-currents, which are always present in the wires, produce a peculiar crackling noise, similar to that produced by a current from a single fluid battery such as a Smee or a Leclanché, not unlike the rushing of broken water. This is due to the polarization of the earth-plate, as the sounds produced by a battery-current are due to the polarization of the negative plate. When auroras are present these earth-currents become very powerful, and the sounds are much intensified. The effects of thunderstorms are very peculiar: a flash of lightning, even though so distant as to be out of sight, will produce a sound; and if it be near enough to be only sheet lightning, it produces, according to Dr. Channing, of Providence, a sound like the quenching of a drop of melted metal in water, or the sound of a distant rocket. Moreover he says that this sound is heard before the flash is seen, proving the existence of some inductive effect in the air prior to the actual discharge. The telephone thus becomes an admirable warning of the approach of a thunderstorm.

Sometimes a peculiar wailing sound is heard, which an imaginative correspondent of mine likened to "the hungry

cry of newly-hatched birds in a nest." I am inclined to think that it is due to the swinging of the wires across the magnetic lines of force of the earth. It is not difficult to conceive that these vibrations may succeed each other in the necessary rhythmic order to produce musical tones.

The wires are never free from sound; and every change of temperature or of the electric condition of the atmosphere is recorded on this delicate apparatus.

The expansion of the iron diaphragm under the influence of the warm and damp breath when the telephone is first raised to the lips preparatory to talk is very marked; it produces a faint rustling shiver.

Immediately on the introduction of the instrument, great anxiety was felt to learn its performance on submarine cables. A telephone was sent to Guernsey, and Mr. Willmot went to Dartmouth, those two places being connected by a cable 60 miles long. Conversation was carried on, the articulation being perfect though slightly muffled. This was a surprise; for it was felt that the static induction of a cable, by its retarding influence, would have prevented articulation by lengthening the waves of electricity and rolling them up as it were. Through the kindness of Messrs. Latimer Clark, Muirhead, and Co. I was able to repeat these experiments on an artificial Atlantic cable, constructed to duplex the direct United-States cable. With Mr. Willmot at one end and myself at the other, there was no difficulty in speaking up to 100 miles, though the muffling effect of induction was evident. Beyond this distance up to 150 miles muffling commenced to seriously impede conversation, and the sounds diminished considerably in strength: it was like talking through a thick respirator. The effect diminished rapidly up to 200 miles, beyond which articulation became impossible, though singing was distinctly heard; indeed singing was heard through the whole length of the cable, 3000 miles long; but this was traced to a secondary cause, it being due to the induction of condenser on condenser. Nevertheless there is no doubt that singing can be heard through a much greater length than speaking, due to the greater regularity of the successive waves of electricity.

I subsequently experimented on the underground wires between Manchester and Liverpool, a distance of about 30 miles;

and through this length we had no difficulty whatever in speaking. Again, between Dublin and Holyhead, through the cable 67 miles long, we spoke with ease, singing coming through with remarkable power and effect. This cable contains 7 distinct conductors. When one wire was used for the telephone, the sounds could be heard on every other wire, but in a feebler degree. When the other wires were working with the ordinary telegraphic apparatus, induction was evident, but not sufficiently intense to stop conversation. Each wire would be surrounded with a wet serving of hemp; but this was not of sufficient conducting-power to entirely screen the effect of induction. The same effect was experienced between Manchester and Liverpool, where the wires are made up into cables of 7 conductors served outside with tarred hemp.

The conclusion that I have come to is, that conversation might be held through a single wire cable 200 miles long with the apparatus that we now have; what new apparatus will do no man is rash enough to predict.

The reason for this surprising result is not difficult to explain:—

Let the disk d , fig. 5, be impressed forwards by a sonorous vibration, it will generate in the coil c a positive current,

Fig. 5.

which, flowing through the line, will pass through the coil c' and attract the disk d' . Now the effect of induction is to retard or prolong the effect of the positive current I ; but the motion of the disk d' has itself produced a current in the reverse direction to the first current; and this neutralizes the prolongation due to induction, and so helps to clear the line

for the next signal, which passes through precisely the same process ; and hence the vibrations of the second disk tend to produce currents which diminish materially the effects of induction, and so render possible conversation to distances that far exceed anticipation.

The extreme delicacy of Bell's apparatus has been shown in various ways ; for instance :—

Extract from a letter from T. A. EDISON, dated November 25, 1877.

“I made a pair of telephones that work with copper diaphragms : it is on the revolving-copper-disk principle of Arago.

“I find that a copper diaphragm may replace the iron in Bell's. Copper must be $\frac{1}{32}$ in. thick. It is very low with copper in both ; but if the receiver is one of the regular kind, and the transmitter is a copper diaphragm, you can carry on conversation with ease both ways ; but with the pair I have made the talking is loud, as I have several dodges on it.”

I repeated these experiments ; but the effect was so feeble as to be scarcely distinguishable, and, although interesting from a scientific point of view, it was of no practical value.

Mr. James Blyth has independently repeated the experiment, and has shown that wood, paper, and india-rubber produce similar effects. These effects are probably due to the fact that diamagnetic bodies have a similar though feebler influence, in varying the direction of lines of magnetic force, to magnetic bodies.

Again, I have spoken distinctly and easily with telephones without any permanent magnet whatever, the core of the coil being of soft iron ; but this effect was probably due to the impurity of the iron, residual magnetism remaining in it. Dr. Blake, of Boston, has spoken easily when the core was a piece of soft iron placed in the direction of the dip.