VII

ON THE FINITE VELOCITY OF PROPAGATION OF ELECTROMAGNETIC ACTIONS

(*Sitzungsbr. d. Berl. Akad. d. Wiss.* Feb. 2, 1888. *Wiedemann's Ann.* **34**, p. 551.)

WHEN variable electric forces act within insulators whose dielectric constants differ appreciably from unity, the polarisations which correspond to these forces exert electromagnetic effects. But it is quite another question whether variable electric forces in air are also accompanied by polarisations capable of exerting electromagnetic effects. We may conclude that, if this question is to be answered in the affirmative, electromagnetic actions must be propagated with a finite velocity.

While I was vainly casting about for experiments which would give a direct answer to the question raised, it occurred to me that it might be possible to test the conclusion, even if the velocity under consideration was considerably greater than that of light. The investigation was arranged according to the following plan:—In the first place, regular progressive waves were to be produced in a straight, stretched wire by means of corresponding rapid oscillations of a primary conductor. Next, a secondary conductor was to be exposed simultaneously to the influence of the waves propagated through the wire and to the direct action of the primary conductor propagated through the air; and thus both actions were to be made to interfere. Finally, such interferences were to be produced at different distances from the primary circuit, so as to find out whether the oscillations of the electric force at great distances would or would not exhibit a retardation of phase, as compared with the oscillations in the neighbourhood of the primary circuit. This plan has proved to be in all respects practicable. The experiments carried out in accordance with it have shown that the inductive action is undoubtedly propagated with a finite velocity. This velocity is greater than the velocity of propagation of electric waves in wires. According to the experiments made up to the present time, the ratio of these velocities is about 45 : 28. From this it follows that the absolute value of the first of these is of the same order as the velocity of light. Nothing can as yet be decided as to the propagation of electrostatic actions.

The Primary and Secondary Conductors

The primary conductor *A A′* (Fig. 25) consisted of two square brass plates, 40 cm. in the side, which were connected by a copper wire 60 cm. long. In the middle of the wire was a spark-gap in which oscillations were produced by very powerful discharges of an induction-coil *J*. The conductor was set up 1·5 metre above the floor, with the wire horizontal and the plane of the plates vertical. We shall denote as the base-line of our experiments a horizontal straight line *r s* passing through the spark-gap and perpendicular to the direction of the primary oscillation. We shall denote as the zero-point a point on this base-line 45 cm. from the spark-gap.

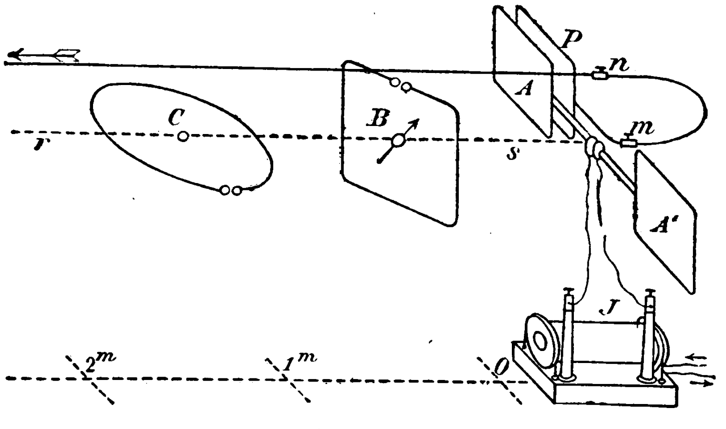

Fig. 25.

The experiments were carried out in a large lecture-room, in which there were no fixtures for a distance of 12 metres in the neighbourhood of the base-line.[1] During the experiments this room was darkened.

The secondary circuit used was sometimes a wire *C* in the form of a circle of 35 cm. radius, sometimes a wire *B* bent into a square of 60 cm. in the side. The spark-gap of both these conductors was adjustable by means of a micrometer-screw ; and in the case of the square conductor the spark-gap was provided with a lens. Both conductors were in resonance with the primary conductor. As calculated from the capacity and coefficient of self-induction of the primary, the (half) period of oscillation of all three conductors amounted to 1·4 hundred-millionths of a second.[2] Still it is doubtful whether the ordinary theory of electric oscillations gives correct results here. But inasmuch as it gives correct values in the case of Leyden jar discharges, we are justified in assuming that its results in the present case will, at any rate, be correct as far as the order of magnitude is concerned.

Let us now consider the influence of the primary oscillation upon the secondary circuit in some of the positions which are of importance in our present investigation. First let us place the secondary conductor with its centre on the base-line and its plane in the vertical plane through the base-line. We shall call this the first position. In this position no sparks are perceived in the secondary circuit. The reason is obvious : the electric force is at all points perpendicular to the direction of the secondary wire.

Now, leaving the centre of the secondary conductor still on the base-line, let it be turned so that its plane is perpendicular to the base-line ; we shall call this the second position. Sparks now appear in the secondary circuit whenever the spark-gap lies above or below the horizontal plane through the base-line ; but no sparks appear when the spark-gap lies in this plane. As the distance from the primary oscillator increases, the length of the sparks diminishes, at first rapidly but afterwards very slowly. I was able to observe the sparks along the whole distance (12 metres) at my disposal, and have no doubt that in larger rooms this distance could be still farther extended. In this position the sparks owe their origin

---

[1] [See Note 12 at end of book.]

[2] See II., p. 50. [See also Note 13 at end of book.]

mainly to the electric force which always acts in the part of the secondary circuit opposite to the spark-gap. The total force may be split up into the electrostatic part and the electromagnetic part; there is no doubt that at short distances the former, at greater distances the latter, preponderates and settles the direction of the total force.

Finally, let the plane of the secondary conductor be brought into the horizontal position, its centre being still on the base-line. We shall call this the third position. If we use the circular conductor, place it with its centre at the zero-point of the base-line, and turn it so that the spark-gap slowly moves around it, we observe the following effects:—In all positions of the spark-gap there is vigorous sparking. The sparks are most powerful and about 6 mm. long when the spark-gap faces the primary conductor; they steadily diminish when the spark-gap is moved away from this position, and attain a minimum value of about 3 mm. on the side farthest from the primary conductor. If the conductor was exposed only to the electrostatic force, we should expect sparking when the spark-gap was on the one side or the other in the neighbourhood of the base-line, but no sparking in the two intermediate positions. Indeed, the direction of the oscillation would be determined by the direction of the force in the portion of the secondary conductor lying opposite to the spark-gap. But upon the oscillation excited by the electrostatic force is superposed the oscillation excited by the electromagnetic force; and here the latter is very powerful, because the electromagnetic force when integrated around the secondary circuit (considered as being closed) gives a finite integral value. The direction of this integrated force of induction is independent of the position of the spark-gap; it opposes the electrostatic force in the part of the secondary conductor which faces AA', but reinforces the electrostatic force in the part which faces away from AA'. Hence the electrostatic and electromagnetic forces assist each other when the spark-gap is turned towards, but they oppose each other when it is turned away from the primary conductor. That it is the electromagnetic force which preponderates in the latter position and determines the direction of the oscillation, may be recognised from the fact that the change from the one state to the other takes place in any position without any extinction of the sparks. For our purpose it is important to make the following observations:—If the spark-gap is rotated to the right or left through 90° from the base-line, it lies at a nodal point with respect to the electrostatic force, and the sparks which appear in it owe their origin entirely to the electromagnetic force, and especially to the fact that the latter, around the closed circuit, is not zero. Hence, in this particular position, we can investigate the electromagnetic effect, even in the neighbourhood of the primary conductor, independently of the electrostatic effect.

A complete demonstration of the above explanations will be found in an earlier paper.[1] Some further evidence in support of these explanations, and of the results arrived at in my earlier paper, will be found in what follows.

The Waves in the Straight Wire

In order to excite in a wire with the aid of our primary oscillations waves suitable for our purpose, we proceed as follows:—Behind the plate *A* we place a plate *P* of the same size. From the latter we carry a copper wire 1 mm. thick to the point *m* on the base-line; from there, in a curve 1 metre long, to the point *n*, which lies 30 cm. above the spark-gap, and thence in a straight line parallel to the base-line for a distance sufficiently great to prevent any fear of disturbance through reflected waves. In my experiments the wire passed through the window, then went about 60 metres freely through the air, and ended in an earth-connection. Special experiments showed that this distance was sufficiently great. If now we bring near to this wire a metallic conductor in the form of a nearly closed circle, we find that the discharges of the induction-coil are accompanied by play of small sparks in the circle. The intensity of the sparks can be altered by altering the distance between the plates *P* and *A*. That the waves in the wire have the same periodic time as the primary oscillations, can be shown by bringing near to the wire one of our tuned secondary conductors; for in these the sparks become more powerful than in any other metallic circuits, whether

---

[1] See V., p. 80.

larger or smaller. That the waves are regular, in respect to space as well as time, can be shown by the formation of stationary waves. In order to produce these, we allow the wire to end freely at some distance from its origin, and bring near to it our secondary conductor in such a position that its plane includes the wire, and that the spark-gap is turned towards the wire. We then observe that at the free end of the wire the sparks in the secondary conductor are very small; they increase in length as we move towards the origin of the wire; at a certain distance, however, they again decrease and sink nearly to zero, after which they again become longer. We have thus found a nodal point. If we now measure the wave-length so found, make the whole length of the wire (reckoned from the point n) equal to a complete multiple of this length, and repeat the experiment, we find that the whole length is now divided up by nodal points into separate waves.[1] If we fix each nodal point separately with all possible care, and indicate its position by means of a paper rider, we see that the distances of these are approximately equal, and that the experiments admit of a fair degree of accuracy.

The nodes can also be distinguished from the antinodes in other ways. If we bring the secondary conductor near to the wire, in such a position that the plane of the former is perpendicular to the latter, and that the spark-gap is neither turned quite towards the wire nor quite away from it, but is in an intermediate position, then our secondary circle is in a suitable position for indicating the existence of forces which are perpendicular to the direction of the wire. Now, when the circle is in such a position, we see that sparks appear at the nodal points, but disappear at the antinodes. If we draw sparks from the wire by means of an insulated conductor, we find that these are somewhat stronger at the nodes than at the antinodes; but the difference is slight, and for the most part can only be perceived when we already know where the nodes and antinodes respectively are situated. The reason why this latter method and other similar ones give no definite result is that the particular waves under consideration have other irregular disturbances superposed upon them. With the aid of our tuned circle, however, we can pick out the disturbances in

---

[1] [See Note 14 at end of book.]

which we are interested, just as particular notes can be picked out of confused noises by means of resonators.

If we cut through the wire at a node, the phenomena along the part between it and the origin are not affected: the waves are even propagated along the part which has been cut off if it is left in its original position, although their strength is diminished.

The fact that the waves can be measured admits of numerous applications. If we replace the copper wire hitherto used by a thicker or thinner copper wire, or by a wire of another metal, the nodal points are found to remain in the same positions. Thus the rate of propagation in all such wires is the same, and we are justified in speaking of it as a definite velocity. Even iron wires are no exception to this general rule; hence the magnetic properties of iron are not called into play by such rapid disturbances. It will be of interest to test the behaviour of electrolytes. The fact that the electrical disturbance in these is bound up with the disturbance of inert matter might lead us to expect a smaller velocity of propagation.[1] Through a tube of 10 mm. diameter, filled with a solution of copper sulphate, the waves would not travel at all; but this may have been due to the resistance being too great. Again, by measuring the wave-lengths, we can determine the relative periods of oscillation of different primary conductors; it should be possible to compare in this way the periods of oscillation of plates, spheres, ellipsoids, etc.

In our particular case the nodal points proved to be very distinct when the wire was cut off at a distance of either 8 metres or 5·5 metres from the zero-point of the base-line. In the former case the positions of the paper riders used for fixing the nodal points were—0·2 m., 2·3 m., 5·1 m., and 8 m.; in the latter case—0·1 m., 2·8 m., and 5·5 m., the distances being measured from the zero-point. From this it appears that the (half) wave-length in the free wire cannot differ much from 2·8 metres. We can scarcely be surprised at finding that the first wave-length, reckoned from *P*, appears smaller than the rest, when we take into consideration the presence of the plate and the bending of the wire. A period of oscilla-

---

[1] [See Note 15 at end of book.]

tion of 1·4 hundred-millionths of a second, and a wave-length of 2·8 metres, gives 200,000 km./sec. as the velocity of electric waves in wires.[1] In the year 1850 Fizeau and Gounelle,[2] making use of a very good method, found for this velocity the value 100,000 km./sec. in iron wires, and 180,000 km./sec. in copper wires. In 1875 W. Siemens,[3] using discharges from Leyden jars, found velocities from 200,000 to 260,000 km./sec. in iron wires. Other determinations can scarcely be taken into consideration. Our result comes in well between the above experimental values. Since it was obtained with the aid of a doubtful theory, we are not justified in publishing it as a new measurement of this same velocity; but, on the other hand, we may conclude, from the accordance between the experimental results, that our calculated value of the period of oscillation is of the right order of magnitude.

Interference between the direct Action and that propagated through the Wire

Let us place the square circuit *B* at the zero-point in our second position, and so that the spark-gap is at the highest point. The waves in the wire now exert no influence; the direct action gives rise to sparks 2 mm. long. If we now bring *B* into the first position by turning it about a vertical axis, it is found conversely that the primary oscillation exercises no direct effect; but the waves in the wire now induce sparks which can be made as long as 2 mm. by bringing *P* near to *A*. In intermediate positions both causes give rise to sparks, and it is thus possible for them, according to their difference in phase, either to reinforce or to weaken each other. Such a phenomenon, in fact, we observe. For, if we adjust the plane of *B* so that its normal towards *A A′* points away from that side of the primary conductor on which the plate *P* is placed, the sparking is even stronger than it is in the principal positions; but if we adjust the plane of *B* so that its normal points towards *P*, the sparks disappear, and only reappear

---

[1] [See Note 16 at end of book.]

[2] Fizeau and Gounelle, *Pogg. Ann.* **80**, p. 158, 1850.

[3] W. Siemens, *Pogg. Ann.* **157**, p. 309, 1876.

when the spark-gap has been considerably shortened. If, under the same conditions, we place the spark-gap at the lowest point of *B*, the disappearance of the sparks takes place when the normal points away from *P*. Further modifications of the experiment—*e.g.* by carrying the wire beneath the secondary conductor—produce just such effects as might be expected from what has above been stated. The phenomenon itself is just what we expected; let us endeavour to make it clear that the action takes place in the sense indicated in our explanation. In order to fix our ideas, let us suppose that the spark-gap is at the highest point, and the normal turned towards *P* (as in the figure). At the particular instant under consideration let the plate *P* have its largest positive charge. The electrostatic force, and therefore the total force, is directed from *A* towards *A′*. The oscillation induced in *B* is determined by the direction of the force in the lower part of *B*. Positive electricity will therefore be urged towards *A′* in the lower part, and away from *A′* in the upper part. Let us now consider the action of the waves. As long as *A* is positively charged, positive electricity flows away from the plate *P*. At the instant under consideration this flow reaches its maximum development in the middle of the first half wave-length of the wire. At a quarter wave-length farther from the origin—that is, in the neighbourhood of our zero-point—it is just beginning to take up this direction (away from the zero-point). Hence at this point the electromagnetic induction urges positive electricity in its neighbourhood towards the origin. In particular, positive electricity in our conductor *B* is thrown into a state of motion in a circle, so that in the upper part it tends to flow towards *A′*, and in the lower part away from *A′*. Thus, in fact, the electrostatic and electromagnetic forces act against one another, and are in approximately the same phase; hence they must more or less annul one another. If we rotate the secondary circle through 90° (through the first position) the direct action changes its sign, but the action of the waves does not; both causes reinforce one another. The same holds good if the conductor *B* is rotated in its own plane until the spark-gap lies at its lowest point.

We now replace the wire *m n* by longer lengths of wire. We observe that this renders the interference more indistinct;

it disappears completely when a piece of wire 250 cm. long is introduced; the sparks are of the same length whether the normal points away from *P* or towards it. If we lengthen the wire still more the difference of behaviour in the various quadrants again exhibits itself, and the extinction of the sparks becomes fairly sharp when 400 cm. of wire is introduced. But there is now this difference—that extinction occurs when the spark-gap is at the top, and the normal points away from *P*. Further lengthening of the wire causes the interference to disappear once more; but it reappears in the original sense when about 6 metres of wire are introduced. These phenomena are obviously explained by the retardation of the waves in the wire, and they also make it certain that the state of affairs in the progressive waves changes sign about every 2·8 metres.

If we wish to produce interference while the secondary circle *C* lies in the third position, we must remove the rectilinear wire from the position in which it has hitherto remained, and carry it along in the horizontal plane through *C*, either on the side towards the plate *A*, or on the side towards the plate *A'*. In practice it is sufficient to stretch the wire loosely, grasp it with insulating tongs, and bring it alternately near one side or the other of *C*. What we observe is as follows:—If the waves are carried along the side on which the plate *P* lies, they annul the sparks which were previously present; if they are carried along the opposite side they strengthen the sparks which were already present. Both results always occur, whatever may be the position of the spark-gap in the circle. We have seen that at the instant when the plate *A* has its strongest positive charge, and when, therefore, the primary current begins to flow away from *A*, the surging at the first nodal point of the rectilinear wire begins to flow away from the origin of the wire. Hence both currents flow round *C* in the same sense when the rectilinear wire lies on the side of *C* which is remote from *A*; in the other case they flow round *C* in opposite senses, and their actions annul one another. The fact that the position of the spark-gap is of no importance confirms our supposition that the direction of the oscillation is here determined by the electromagnetic force. The interferences which have just been described also change their sign when 400 cm. of wire, instead of 100 cm., is introduced between the points *m* and *n*.

I have also produced interferences in positions in which the centre of the secondary circle lay outside the base-line; but for our present purpose these are only of importance inasmuch as they throughout confirmed our fundamental views.

Interference at Various Distances

Interferences can be produced at greater distances in the same way as at the zero-point. In order that they may be distinct, care must be taken that the action of the waves in the wire is in all cases of about the same magnitude as the direct action. This can be secured by increasing the distance between *P* and *A*. Now very little consideration will show that, if the action is propagated through the air with infinite velocity, it must interfere with the waves in the wire in opposite senses at distances of half a wave-length (*i.e.* 2·8 metres) along the wire. Again, if the action is propagated through the air with the same velocity as that of the waves in the wire, the two will interfere in the same way at all distances. Lastly, if the action is propagated through the air with a velocity which is finite, but different from that of the waves in the wire, the nature of the interference will alternate, but at distances which are farther than 2·8 metres apart.

In order to find out what actually took place, I first made use of interferences of the kind which were observed in passing from the first into the second position. The spark-gap was at the top. At first I limited myself to distances up to 8 metres from the zero-point. At the end of each half-metre along this position the secondary conductor was set up and examined in order to see whether any difference could be observed at the spark-gap according as the normal pointed towards *P* or away from it. If there was no such difference, the result of the experiment was indicated by the symbol 0. If the sparks were smaller when the normal pointed towards *P*, then this showed an interference which was represented by the symbol +. The symbol — was used to indicate an interference when the normal pointed towards the other side. In order to multiply the experiments I frequently repeated them, making the wire *m n* 50 cm. longer each time, and thus lengthening it gradually from 100 cm. to 600 cm. The results of my experiments are contained in the following summary which will easily be understood :—

	0		1		2		3		4		5		6		7		8
100	+	+	0	−	−	−	−	−	0	0	0	0	0	+	+	+	+
150	+	0	−	−	−	−	0	0	0	0	0	+	+	+	+	+	0
200	0	−	−	−	−	−	0	+	+	+	+	+	0	0	0	0	0
250	0	−	−	−	−	0	0	+	+	+	+	0	0	0	0	0	0
300	−	−	−	−	0	+	+	+	+	+	0	0	0	0	−	−	−
350	−	−	0	+	+	+	+	+	+	0	0	0	−	−	−	−	−
400	−	−	0	+	+	+	+	0	0	0	0	−	−	−	−	−	−
450	−	0	+	+	+	+	+	0	0	0	−	−	−	−	−	−	0
500	−	0	+	+	+	+	0	−	−	−	−	−	0	0	0	0	+
550	0	+	+	+	+	0	0	−	−	−	−	−	0	0	0	0	+
600	+	+	+	+	0	0	−	−	−	−	−	0	0	+	+	+	+

According to this it might almost appear as if the interferences changed sign at every half wave-length of the waves in the wire.[1] But, in the first place, we notice that this does not exactly happen. If it did, then the symbol 0 should recur at the distances 1 m., 3·8 m., 6·6 m., whereas it obviously recurs less frequently. In the second place, we notice that the retardation of phase proceeds more rapidly in the neighbourhood of the origin than at a distance from it. All the rows agree in showing this. An alteration in the rate of propagation is not probable. We can with much better reason attribute this phenomenon to the fact that we are making use of the total force (*Gesammtkraft*), which can be split up into the electrostatic force and the electromagnetic. Now, according to theory, it is probable that the former, which preponderates in the neighbourhood of the primary oscillation, is propagated more rapidly than the latter, which is almost the only factor of importance at a distance. In order first to settle what actually happens at a greater distance, I have extended the experiments to a distance of 12 metres, for at any

---

[1] [See Note 17 at end of book.]

rate three values of the length *m n*. I must admit that this required rather an effort. Here are the results :—

	0	1	2	3	4	5	6	7	8	9	10	11	12
100	+	0	−	−	0	0	0	+	+	+	+	+	0
250	0	−	−	0	+	+	0	0	0	0	−	−	−
400	−	0	+	+	0	0	−	−	−	−	0	0	0

If we assume that at considerable distances the electromagnetic action alone is effective, then we should conclude from these observations that the interference of this action with the waves in the wires only changes its sign every 7 metres.

In order now to investigate the electromagnetic force in the neighbourhood of the primary oscillation (where the phenomena are more distinct) as well, I made use of the interferences which occur in the third position when the spark-gap is rotated 90° away from the base-line. The sense of the interference at the zero-point has already been stated, and this sense will be indicated by the symbol —, whereas the symbol + will be used to denote an interference by conducting the waves past the side of *C* which is remote from *P*. This choice of the symbols will be in accord with the way in which we have hitherto used them. For since the electromagnetic force is opposed to the total force at the zero-point, our first table would also begin with the symbol —, provided that the influence of the electrostatic force could have been eliminated. Now experiment shows, in the first place, that interference still takes place up to a distance of 3 metres, and that it is of the same sign as at the zero-point. This experiment, repeated often and never with an ambiguous result, is sufficient to prove the finite rate of propagation of the electromagnetic action. Unfortunately the experiments could not be extended to a greater distance than 4 metres, on account of the feeble nature of the sparks. Here, again, I repeated the experiments with variable lengths of the wire *m n*, so as to be able to verify the retardation of phase along this portion of the wire. The results are given in the following summary :—

	0	1	2	3	4
100	−	−	−	−	O
150	−	−	O	O	O
200	O	O	O	+	+
250	O	+	+	+	+
300	+	+	+	+	+
350	+	+	+	+	O
400	+	+	+	+	O
450	+	+	+	O	O
500	+	+	O	O	O
550	+	O	O	O	−
600	O	−	−	−	−

A discussion of these results shows that here, again, the phase of the interference alters as the distance increases, so that a reversal of sign might be expected at a distance of 7–8 metres.

But this result is much more plainly shown by combining the results of the second and third summary—using the data of the latter up to a distance of 4 metres, and of the former for greater distances. In the first of these intervals we thus avoid the action of the electrostatic force by reason of the peculiar position of our secondary conductor; in the second this action drops out of account, owing to the rapid weakening of that force. We should expect the observations of both intervals to fit into one another without any break, and our expectation is confirmed. We thus obtain by collating the symbols the following table for the interference of the electromagnetic force with the action of the waves in the wire:—

	0	1	2	3	4	5	6	7	8	9	10	11	12
100	−	−	−	−	O	O	O	+	+	+	+	+	O
250	O	+	+	+	+	+	O	O	O	O	−	−	−
400	+	+	+	+	O	O	−	−	−	−	O	O	O

From this table I draw the following conclusions:—

1. The interference does not change sign every 2·8 metres. Therefore the electromagnetic actions are not propagated with infinite velocity.

2. The interference, however, is not in the same phase at all points. Therefore the electromagnetic actions do not spread out in air with the same velocity as the electric waves in wires.

3. A gradual retardation of the waves in the wire has the

effect of shifting any particular phase of the interference towards the origin of the waves. From the direction of this shifting it follows that of the two different rates of propagation that through air is the more rapid. For if by retardation of one of the two actions we bring about an earlier coincidence of both, then we must have retarded the slower one.

4. At distances of every 7·5 metres the sign of the interference changes from + to −. Hence, after proceeding every 7·5 metres, the electromagnetic action outruns each time a wave in the wire. While the former travelled 7·5 metres, the latter travelled $7{\cdot}5 - 2{\cdot}8 = 4{\cdot}7$ metres. The ratio of the two velocities is therefore as 75 : 47, and the half wave-length of the electromagnetic action in air is $2{\cdot}8 \times 75/47 = 4{\cdot}5$ metres. Since this distance is traversed in 1·4 hundred-millionths of a second, it follows that the absolute velocity of propagation in air is 320,000 km. per second. This result only holds good as far as the order of magnitude is concerned; still the actual value can scarcely be greater than half as much again, and can scarcely be less than two-thirds of the value stated. The actual value can only be determined by experiment when we are able to determine the velocity of electricity in wires more accurately than has hitherto been the case.

Since the interferences undoubtedly change sign after 2·8 metres in the neighbourhood of the primary oscillation, we might conclude that the electrostatic force which here predominates is propagated with infinite velocity. But this conclusion would in the main depend upon a single change of phase, and this one change can be explained (apart from any retardation of phase) by the fact that, at some distance from the primary oscillation, the amplitude of the total force undergoes a change of sign. If the absolute velocity of the electrostatic force remains for the present unknown, there may yet be adduced definite reasons for believing that the electrostatic and electromagnetic forces possess different velocities. The first reason is that the total force does not vanish at any point along the base-line. Since the electrostatic force preponderates at small distances, and the electromagnetic force at greater distances, they must in some intermediate position be equal and opposite, and, inasmuch as they do not annul one another, they must reach this position at different times.

The second reason is derived from the propagation of the force throughout the whole surrounding space. In a previous paper[1] it has already been shown how the direction of the force at any point whatever can be determined. The distribution of the force was there described, and it was remarked that there were four points in the horizontal plane, about 1·2 metre before and behind the outer edges of our plates A and A', at which no definite direction could be assigned to the force, but that the force here acts with about the same strength in all directions. The only apparent interpretation of this is that the electrostatic and electromagnetic components here meet one another at right angles, and are about equal in strength but differ notably in phase; thus they do not combine to produce a resultant rectilinear oscillation, but a resultant which during each oscillation passes through all points of the compass.

The fact that different components of the total force possess different velocities is also of importance, inasmuch as it provides a proof (independent of those previously mentioned) that at least one of these components must be propagated with finite velocity.

Conclusions

More or less important improvements in the quantitative results of this first experiment may result from further experiments in the same direction; but the path which they must follow may be said to be already made, and we may now regard it as having been proved that the inductive action is propagated with finite velocity. Sundry conclusions follow from the results thus obtained, and to some of these I wish to draw attention.

1. The most direct conclusion is the confirmation of Faraday's view, according to which the electric forces are polarisations existing independently in space. For in the phenomena which we have investigated such forces persist in space even after the causes which have given rise to them have disappeared. Hence these forces are not simply parts or attributes of their causes, but they correspond to changed con-

---

[1] See V., p. 80.

ditions of space. The mathematical character of these conditions justifies us then in denoting them as polarisations, whatever the nature of these polarisations may be.

2. It is certainly remarkable that the proof of a finite rate of propagation should have been first brought forward in the case of a force which diminishes in inverse proportion to the distance, and not to the square of the distance. But it is worth while pointing out that this proof must also affect such forces as are inversely proportional to the square of the distance. For we know that the ponderomotive attraction between currents and their magnetic actions are connected by the principle of the conservation of energy with their inductive actions in the strictest way, the relation being apparently that of action and reaction. If this relation is not merely a deceptive semblance, it is not easy to understand how the one action can be propagated with a finite and the other with an infinite velocity.

3. There are already many reasons for believing that the transversal waves of light are electromagnetic waves; a firm foundation for this hypothesis is furnished by showing the actual existence in free space of electromagnetic transversal waves which are propagated with a velocity akin to that of light. And a method presents itself by which this important view may finally be confirmed or disproved. For it now appears to be possible to study experimentally the properties of electromagnetic transversal waves, and to compare these with the properties of light waves.

4. The hitherto undecided questions of electromagnetics which relate to unclosed currents should now be more easily attacked and solved. Some of these questions, indeed, are directly settled by the results which have already been obtained. In so far as electromagnetics only lacks certain constants, these results might even suffice to decide between the various conflicting theories, assuming that at least one of them is correct.

Nevertheless, I do not at present propose to go into these applications, for I wish first to await the outcome of further experiments which are evidently suggested in great number by our method.