XII

ON THE MECHANICAL ACTION OF ELECTRIC WAVES IN WIRES

(*Wiedemann's Ann.* **42**, p. 407, 1891.)

THE investigation of the mechanical forces to which a conductor is subjected under the action of a series of electric waves appeared to me to be desirable for several reasons. In the first place, these forces might supply a means of investigating such waves quantitatively, provided that the effects observed were of sufficient magnitude and regularity. Hitherto almost the only quantitative determinations have been based on the heating effect of the waves. In the hands of Herren Rubens and Ritter this method has given excellent results;[1] but the observation of the mechanical forces offers in many cases the advantage of simplicity. In the second place, by examining the nature and distribution of the mechanical forces, I hoped to find a means of demonstrating the existence of the magnetic force in addition to the electric force. Only the latter has manifested itself in the observations hitherto made;[2] and as the ordinary methods of detecting magnetic force are of no avail here, it appeared to be worth while trying whether a new method would prove more serviceable. In the third and last place—and this was more especially the object of the investigation—I hoped to be able to devise some way of making observations on waves in free air,—that is to say, in such a manner that any disturbances which might be observed could

[1] H. Rubens and R. Ritter, *Wied. Ann.* **40**, p. 55, 1890.

[2] If I have myself on former occasions happened to speak of the observation of nodes of the magnetic waves, this mode of expression was only justified by theory and not required by experiment.

in no wise be referred to any action-at-a-distance. This last hope was frustrated by the feebleness of the effects produced under the circumstances. I had to content myself with examining the effects produced by waves travelling along wires, although in so doing the most important object of the experiments was missed. The mechanical actions produced by waves in wires may be and will be regarded as being due to attractions caused by the electrification of the wires and by the currents flowing in them. For this reason researches on waves in wires cannot be made use of to decide between the older and the newer views. If, however, we start from the point of view from which waves in wires are regarded simply as a special form of waves travelling in air, it is a matter of indifference whether we make the one form or the other the object of our experiments.

1. *The System of Waves Employed*

After trying several ways of disposing the waves, and after obtaining results which in the main were concordant, I decided to adhere to Herr Lecher's arrangement as being the neatest and the most suitable for the investigation.[1] Fig. 37 shows the form thereof.

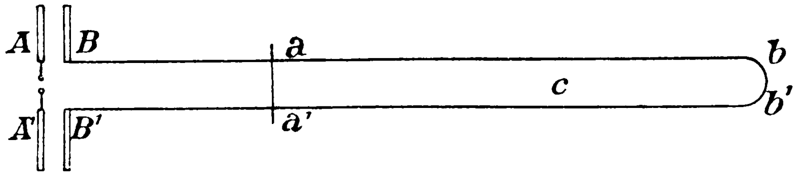

Fig. 37.

$A\,A'$ is the same conductor which was always used before as the primary conductor, and consists of two square plates, each 40 cm. in the side, connected by a wire 60 cm. long which contains a 2 mm. spark-gap. A small induction-coil was used as an exciter; this was supplied with current from two accumulators, and its maximum spark-length was only 4 cm. Single discharges of this smaller apparatus were certainly less efficient than those of a larger induction-coil, but this

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[1] E. Lecher, *Wied. Ann.* **41**, p. 850, 1890.

drawback was more than compensated for by the more rapid succession of discharges. Opposite the plates A and A', and at a distance of 10 cm. from them, stood the plates B and B', from which two parallel wires, about 30 cm. apart, are led to a distance of 6·8 metres, and there are connected together between b and b'. At a variable distance aa' from their origin these wires are placed in communication with each other by means of a second connection or *bridge*. When this bridge is in a certain position, at a distance of about 1·2 metre from BB', there takes place in the interval between aa' and bb' a very energetic oscillation. This indicates the half wave-length of a stationary wave, and, as Herr Lecher has shown, it is produced by resonance between this oscillation itself and the primary oscillation, which here takes place in the interval between AA' on the one hand, and $Baa'B'$ on the other hand. Any shifting of the bridge increases one of the two periods of oscillation, and at the same time diminishes the other; hence the peculiar definiteness of adjustment with this arrangement. Besides its general excellence it offers for our present purpose several special advantages. Since the forces to be observed are very small, we have to protect carefully the conductors which are subjected to them from external electrostatic effects. With the arrangement here used this is possible, because the wires, which we must necessarily place near the test-body, form a connected conducting system. If in our experiments we surround the working parts (of the apparatus) with a wire network, and connect this with the nodal points at aa' and bb', the protection is made complete without interfering with the vibration. Hence the experiments are carried out in this way. Again, since the conductors which are to be subjected to the forces do not, like the resonators previously used, pick out a definite vibration from the whole disturbance, we could only expect confused results if we did not otherwise take care to produce a simple oscillation of definite wave-length and with nodes in known positions. This condition is fulfilled in the above arrangement; for there can be no doubt that the points aa' and bb' are nodal points of all oscillations excited between them, and that among these only the longest oscillation, strengthened by resonance, rises to a considerable magnitude. Clearly, we do not narrow the scope of the experiments by contenting ourselves with the investigation of half a wave-length. Finally, the conditions of our oscillation are practically the same whether the two wires are stretched straight, or whether they are bent side by side in any desired way; just as, in the case of acoustic vibrations of air in tubes, it is not of much importance whether the tubes are straight or crooked. We can thus easily bring our oscillation into all possible positions with respect to the test-body which is held in a fixed position. As a matter of fact, the various relative positions were always obtained by shifting the wire, even in cases in which it may appear from the text that the test-body had been shifted.

2. *The Electric Force*

For the purpose of measuring the mechanical action of the electric force, I made use of a small cylindrical tube of gold paper 5·5 cm. long, and 0·7 cm. in diameter. This was suspended by a silk fibre with its axis horizontal; a very small magnet gave the tube a definite position of rest, and a deviation from this position was measured by means of a small mirror. The whole system hung in a glass case, as shown in Fig. 38. When the apparatus was subjected to the action of the oscillation, the needle tended to set along the mean direction of the electric force, and was thus deflected from the position of rest. In order to increase these deflections I brought the two wires in the neighbourhood of the apparatus nearer to one another and to the test-body—in fact, within a few centimetres; and in order to strengthen the action I attached small plates to the wires opposite to the ends of the test-body, as shown for one special case in the figure. Under

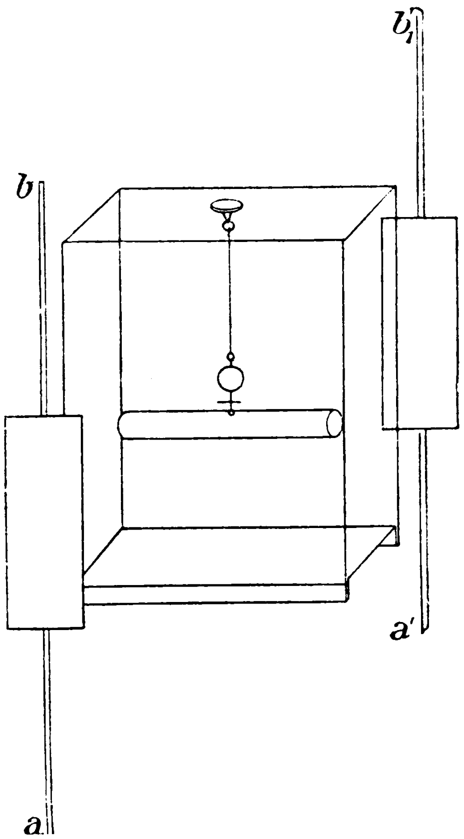

Fig. 38.

these circumstances first deflections of 100 scale divisions and above could be obtained. These first throws exhibited a satisfactory regularity; when the same experiment was repeated several times, the separate results only differed from one another by a few per cent. The differences between single discharges ought to be much greater, but the throw of the needle gives the mean effect of very many discharges. In order to show how these throws can be used in quantitative experiments I here quote two series of observations. The first of these is intended to illustrate the effect of resonance. The apparatus was set up at c at the antinode of an oscillation, and the wires ab and $a'b'$ were brought near to it, as shown in Fig. 38. The bridge $a\,a'$ was now placed at various distances e from the origin BB' of the wires, the induction-apparatus was put into action, and the magnitude i of the throw measured. The respective values of e and i in the neighbourhood of the maximum were:—

$e=$	80	90	100	110	120	130	140	150	160 cm.
$i=$	5·3	10·0	21·8	51·2	44·1	19·3	10·3	5·7	4·2 div.

When the throws are represented graphically it is seen that their course is regular and exhibits a pronounced maximum between 110 and 120 cm. In fact, the throws reach their largest value $i=60{\cdot}6$ scale divisions at $e=114$ cm.

The second series of observations was intended to exhibit the decrease in the intensity of the oscillation from the antinode c to the node b. For this purpose the distance was divided into 12 equal divisions, and the apparatus was introduced at the 13 end-points. The following first throws i were obtained:—

1	2	3	4	5	6	7	8	9	10	11	12	13
80·5	80·5	79·0	77·0	65·6	57·8	50·0	38·5	27·5	17·5	7·0	1·0	0

These values again give a sufficiently smooth curve and enable us to form an idea of the nature of the oscillation, and to convince ourselves that it differs appreciably from the simple sine-oscillation.

Other experiments which I planned had reference to the direction of the electric force in the neighbourhood of the wires. These experiments gave no fresh information beyond what might be regarded as already settled. In the interval between the wires the needle tended to set along the shortest line between the two wires; outside this space it tended to take up the direction towards the nearest wire. Thus there was always an apparent attraction to be observed between the ends of the tube and the nearest parts of the wires.

3. *The Magnetic Force*

In order to investigate the magnetic force I made use of a circular hoop of aluminium wire. The diameter of this hoop was 65 mm., and that of the wire was 2 mm. The hoop was suspended so that it could turn about a vertical diameter, and, like the cylinder in the last section, was provided with a magnet, mirror, and glass case. Fig. 39 gives a sketch of the apparatus used.

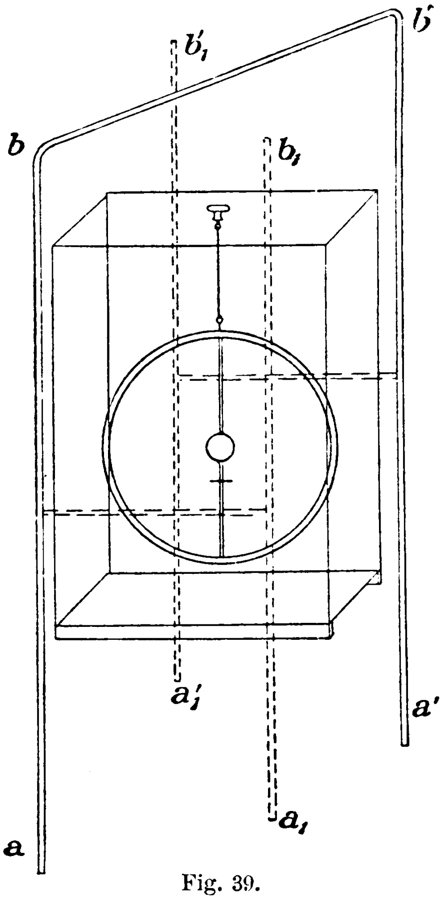

Fig. 39.

If we disregard for a moment our knowledge of the magnetic force we should expect that, under the influence of the oscillation, the hoop would behave just like the cylinder, and therefore that the direction of the parts which are farthest from the axis of rotation, *i.e.* that the horizontal diameter of the hoop would play the same part as the axis of length of the cylinder. We should therefore expect the end-points of the horizontal diameter would everywhere be attracted by the nearest parts of the wires through which the waves are passing, and that this action would be strongest at the antinode of the oscillation, and would cease in the neighbourhood of the nodes where the electric force itself disappears. But if we actually hang up the hoop at the node $b\,b'$, in the manner shown in Fig. 39, we observe other and unexpected phenomena. In the first place, the ring does not remain at rest under the influence of the oscillation, but exhibits deflections of the same order of magnitude as those shown by the cylinder at the antinode of the oscillation. In the second place, the deflection does not indicate an attraction but a repulsion between the neighbouring points of the hoop and the wires. That the repulsion is a consequence of the oscillation itself is shown by the fact that its magnitude is found to be determined by resonance, according to the same law as that of the electrical action. If we leave the hoop inside the bent wire *b b′*, but alter the relative positions of the two, we find that the horizontal diameter always, and from all sides, endeavours to take up a position perpendicular to the plane of the bent wire.

After these experiments alone, and apart from any knowledge obtained otherwise, we may therefore assert that, in addition to the electric oscillation, there is present an oscillation of another kind whose nodal points do not coincide with those of the electric oscillation, and that this oscillation, like the electrical one, exhibits itself as a directive change of space-conditions, but that the characteristic direction of the new oscillation is perpendicular to the electrical one.

We may indeed, going beyond mere observation, at once identify the new oscillation with the magnetic oscillation required by theory. The rapidly alternating magnetic force must induce in the closed hoop a current alternating rhythmically with it, and the reaction between these causes the deflection of the loop. The magnetic force has its maximum value at the nodes of the electric oscillation, and just there its direction is perpendicular to the plane of the bent wire. We can most easily understand the repulsion between the fixed wires and the neighbouring parts of the hoop by regarding it as the effect of currents flowing along these paths. The current deduced in the hoop must continually annul the effect of the inducing current in the interior of the hoop; it must therefore at every instant be in the opposite direction to the latter, and must accordingly be repelled by it.

All the remaining phenomena of disturbance which are observed with the suspended hoop, can without difficulty be connected with the above explanation. Under certain circumstances complications arise. For example, if we leave the arrangement in the state shown in Fig. 39, but move the hoop from the node *b b′* towards the antinode of the oscillation, the repulsion rapidly diminishes; at a certain distance it becomes zero, and then changes into an attraction which increases until we arrive at the antinode. In one special case, for example, the repulsion at *b b′* amounted to 20 scale divisions, disappeared at a distance of 95 cm. from the end, and then changed into an attraction of which the maximum value was measured by 44 scale divisions. Clearly these changes are not to be explained by the behaviour of the magnetic force alone, but by the joint action of the magnetic with the electric force; of these the latter preponderates considerably at *c*, the former at *b b′*. By eliminating the electric force we can confirm this view and follow the course of the magnetic oscillation. For this purpose we set up two other wires parallel to the wires *a b* and *a′b′*, but only 20 cm. long, and in such a position that they are symmetrical towards the wires *ab* and *a′b′* with reference to the position of rest of the hoop, as shown by the dotted lines $a_1 b_1$ and $a_1' b_1'$ in Fig. 40. We connect *ab* with $a_1 b_1$ and *a′ b′* with $a_1' b_1'$. Clearly this almost annuls the electric action, but scarcely affects the magnetic. In fact, we now observe that at all distances the movable ring is repelled from the fixed wires. This repulsion diminishes continuously from the ends towards the middle of the oscillation; it there reaches a minimum which, in the particular instance referred to, amounted to 4 scale divisions. If the electric oscillation were a real sine-oscillation, the magnetic force would necessarily vanish at its antinode; but we saw at once, from the distribution of the electric force, that this simple assumption did not hold good, and so we can easily understand the existence of a residual magnetic force at the antinode of the oscillation.

As required by theory, the mechanical effects of the electric and of the magnetic force prove to be, in general, of the same order of magnitude; the preponderance of the one over the other in each particular case is mainly determined by the proportions of the neighbouring parts of the ring and of the fixed conductors. The more these approximate to the state of infinitely thin wires, the more the magnetic force comes into prominence; the broader the surfaces which are attached to them, the more is the magnetic force overpowered by the electric force. It is evident, even from the simple examples of forms of conductor which we have chosen for the detailed investigation, that a conductor of any form whatever inside a train of electromagnetic waves must be subjected to the action of forces which are complicated and not always easy to understand.