Absorption of Electric Waves along Wires by a Terminal Bridge

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1896 Proc. Phys. Soc. London 15 23

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III. *Absorption of Electric Waves along Wires by a Terminal Bridge.* By EDWIN H. BARTON, D.Sc., F.R.S.E., Senior Lecturer in Physics at University College, Nottingham, and GEO. B. BRYAN, B.Sc., "1851 Exhibition" Research Scholar*.

IN the discussion on Mr. Yule's electrical paper last year†, one of us stated his intention of endeavouring to realise experimentally the extinction of electric waves along wires on their arrival at the end of the line, the urgent desirability of this having been felt by several investigators‡. The question is probably of interest also in connexion with Telephony. This task, small as it may seem, we had no opportunity to attack till this summer. The adoption of a resistance-bridge for the absorption of the electric waves was originally suggested by Mr. Oliver Heaviside's mathematical proof§ that, given a bridge of suitable resistance at the end of a line, then the waves arriving there would be immediately absorbed; "the electricity is all gobbled up at once, so to speak"||. And, a few preliminary difficulties being overcome, this important theoretical conclusion readily received experimental confirmation.

Experimental Arrangement.—The electric vibrations were generated by an oscillator of the type and size previously used by Mr. V. Bjerknes¶ and others. The waves, about $8\frac{1}{2}$ metres long, were propagated along a "line" consisting of a pair of parallel copper wires 1.5 mm. in diameter and 8 cm.

* Read November 13, 1896.

† G. U. Yule, "On the Passage of an Oscillator Wave-Train through a Plate of Conducting Dielectric," Proc. Phys. Soc. vol. xiii. pp. 358-392 (1895); Phil. Mag. [5] xxxix. p. 309.

‡ See e.g. J. von Geitler, pp. 7-8, 'Inaugural Dissertation,' Bonn, 1893; E. H. Barton, pp. 70-71, Proc. Roy. Soc. vol. lvii. 1894; G. U. Yule, Proc. Phys. Soc. t. c. pp. 384-387; Phil. Mag. t. c. pp. 334-337.

§ 'Electrical Papers,' vol. ii. pp. 127 and 132-133.

|| *Loc. cit.* p. 127.

¶ V. Bjerknes, Wied. Ann. vol. xlv. pp. 519-520 (1891); E. H. Barton, Proc. Roy. Soc. vol. liv. p. 86 (1893); G. U. Yule, Proc. Roy. Soc. vol. liv. p. 97 (1893).

apart. The waves were detected and relatively measured by an attraction-electrometer made on the principle of that devised by Herr von Geitler*. The length of the line to the electrometer was 116 m. This instrument has a needle of aluminium foil suspended by a quartz fibre between disks which may be connected to the respective wires of the line. On the passage of a wave-train the needle, initially uncharged, is charged inductively, and its ends are accordingly attracted to the disks whatever the sign of their potential-difference.

The electrometer therefore responds by a deflexion of the needle towards its disks. Let us call this a positive deflexion. In addition to the needle just described, and fixed to it in the same vertical plane, is a second similar one, but with its pair of attracting disks so situated that when they alone are connected to the line a negative deflexion ensues. When both needles have their respective disks connected to the line the electrometer is said to be used differentially. When so used, and with the instrument in adjustment, no deflexion is produced by the simple passage of a wave-train. Suppose now, owing to anything on the line which causes reflexion, stationary waves are produced at the electrometer. Then, provided one needle be connected to a point on the line which is a *node* for the waves, and the other be at a *loop*, the electrometer must give a deflexion and thus prove that *reflexion* of the waves has occurred. It is easily seen that when a single needle is used the first throw is proportional to the time-integral of the square of the potential-difference of the two leads of the line at the place to which the disks are connected.

The electrometer-needle carried a light plane mirror, and the throws were read by a distant telescope and scale.

Theory of Absorption.—Mr. Heaviside's † theory shows that in the case of plane electric waves proceeding along parallel leads to a bridge at the end of the line, the ratio of the potential-differences of the two leads due respectively to the reflected and incident waves is given by

$$\rho = \frac{R - Lv}{R + Lv}, \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

* Wied. *Ann.* vol. xlix. p. 188 (1893).

† 'Electrical Papers,' vol. ii. pp. 132-133.

where ρ is the ratio in question, or *reflexion coefficient*, R is the resistance of the bridge, which must be of negligible inductance, L is the inductance per unit length of the line, and v is the velocity of light. Electromagnetic units are to be understood throughout.

Thus,

$$\rho = -1, \text{ for } R=0, (2)$$

$$\rho = +1, \text{ for } R=\infty, (3)$$

$$\text{and } \rho = 0, \text{ for } R=Lv. (4)$$

Now $v=3 \times 10^{10}$ cm. per sec. nearly, and in the present case $L=4 \log_e \left(\frac{8}{0.075} \right) = 18.68$ nearly. Hence the critical value of R to give complete absorption is,

$$R=3 \times 10^{10} \times 18.68 \text{ absolute units of resistance} = 560 \text{ ohms. } (5)$$

Details of Bridge. At first an ordinary resistance-box was used as a bridge across the two wires of the line. But this was soon rejected lest the faces of the two bars at a plug opening should act as the plates of a condenser of appreciable capacity, which is inadmissible in the bridge desired. We next wound a small coil non-inductively on a bobbin in the usual manner and used it without any box or screw terminals. It was of well-covered wire and further insulated by thorough soaking in paraffin-wax both before and after winding. But this too proved unsatisfactory. For a time it stood, but then the insulation broke down and sparks were seen to pass between different turns of the wire. It was accordingly abandoned.

The simple expedient of making an electrical resistance by rubbing a common lead pencil on a disk of ground glass, small pieces of tin-foil gripped on by binding-screws forming the terminals, was then tried, and seemed in every way satisfactory. The electrostatic capacity of the terminals was proved to be negligible by testing such a disk and screws without any pencil. In this case no reflexion of the waves could be detected. Moreover, by making the track of the pencil-marks between the terminals very wide, the self-induction of the bridge was reduced to a minimum. It was also found easy to adjust the resistance to a few ohms

and to restore it nearly to its original value after the change which spontaneously occurred in it from day to day. Three bridges of this type were used, of resistances 261, 549 to 560, and 1336 to 1355 ohms. Let these be denoted respectively by the letters F, G, and H. Finally, since the pencil-markings on the glass form an extremely thin sheet, the resistance may be assumed to be practically the same to high-frequency waves as to the steady current by which they were measured on the Post-office box.

Experiments.—The oscillator emits rapidly-damped electric vibrations, only the first dozen, say, being appreciable. We thus have, advancing along the line with the speed of light, a damped wave-train, its large end, or head, leading and its tail, after about twelve waves, being negligibly small. Suppose now one needle of the electrometer to be connected to the line and a bridge of no resistance to be placed at the end of the line a little beyond the electrometer. We shall then have, at the electrometer, stationary waves due to interference between the incident waves and those reflected at the bridge. Hence, if a series of readings be taken with the electrometer at different distances from the end of the line the throws will be found to periodically wax and wane. But when the bridge is distant a few wave-lengths from the electrometer, we have the head of the wave-train interfering with the tail only. And with somewhat greater distances between electrometer and bridge the interferences of the waves and, consequently, the waxing and waning of the electrometer-throws cease to be appreciable. Thus, if the distances between electrometer and terminal bridge are plotted as abscissæ and electrometer throws as ordinates, we should expect the experiment to yield a damped wavy curve. And this is the case, as first shown by Mr. V. Bjerknes*, and utilized by him and his successors to determine the wave-length of the oscillations in use. The result of this experiment in our case is shown by the full-line curve E on the diagram.

In the case just considered the reflexion coefficient, ρ , of the bridge is -1 , as shown by equation (2). The waves are therefore unchanged in magnitude by the act of reflexion. Turn now to the general case of a precisely similar experiment

* Wied. Ann. vol. xliv. pp. 522-523 (1891).

Curves showing Interference due to Reflexion.
 Line G G, being almost straight, indicates complete absorption by the corresponding bridge.

with a terminal bridge for which ρ is finite and less than unity. In this case, obviously, theory predicts a curve of similar form, wavy and damped, but lying between narrower limits, since the reflected wave is now always smaller than the incident one. Such an experimental result may, therefore, be accepted as proof that the bridge in use diminishes the wave in the act of reflexion.

Further,

for $R < Lv$, ρ has a negative value, . . . (6)

and consequently the maxima and minima of the curves occur for the same values of the abscissæ as when $R=0$. This is seen to be the case with the dotted curve, F, on the diagram, obtained with the bridge whose resistance was 261 ohms.

Again,

for $R > Lv$, ρ has a positive value; . . . (7)

hence this curve is, broadly speaking, an inversion of that just considered, the maxima occurring for those values of the abscissæ at which the minima of the curve for $R=0$ occurred, and *vice versa*. This is exemplified in the dotted curve, H, on the diagram, resulting from the experiment with the bridge whose resistance was of the order 1350 ohms.

Finally, we have

for $R=Lv$, $\rho=0$ (8)

In this case, since no waves are reflected, no stationary waves can obtain, and consequently no waxing and waning of the electrometer-throws can occur. Thus theory predicts a straight line as the outcome of an experiment with a bridge of this critical resistance. This is approximately the case with the full-line curve, G, on the diagram, obtained with the bridge whose resistance was of the order 560 ohms, the theoretical value of the critical resistance for the line used.

Of course an absolutely straight line cannot be expected, since the sparks in the oscillator vary slightly. For this reason, throughout the experiments hitherto considered the throws with the bridge under examination at any desired distance beyond the electrometer were alternated with those obtained with a no-resistance bridge at the standard distance of a quarter-wave-length beyond. And the ordinates of the curves on the diagram represent, not the actual electrometer-

throws with the bridge and distance in question, but the ratio of these to those obtained under the standard conditions just described. Thus the maximum ordinate in the diagram is unity, all the curves are reduced to the same scale, and the errors due to variations of the sparking at the oscillator are in great measure eliminated. In the above experiments the electrometer was used as a single-needle instrument, and the throws obtained varied up to 100 scale-divisions.

As a further test of the non-reflexion of waves by the bridge G, the electrometer was afterwards used differentially, the upper and lower needles having their disks attached to points on the line a quarter-wave-length apart. The bridges were placed at the end of the line 0.25 m. beyond the second needle. With a no-resistance bridge the throws were positive and of the order 50 scale-divisions; with a simple disconnection ("infinity bridge") the throws were of the same order but negative. The bridges F and H gave smaller throws, positive and negative respectively. The bridge G also appeared to yield a small throw; but this was no larger than might be due to a creep of the zero or an imperfection in the adjustment of the electrometer-needles. The use of the differential electrometer is thus seen to confirm the results of the experiments conducted with a single needle.

It should be noted that this paper deals only with the absorption of waves by *terminal* bridges; no *intermediate* resistance-bridge will absorb all the waves arriving there. The reflexion and transmission coefficients ρ' and τ' for an intermediate bridge of resistance R are given by *

$$\rho' = \frac{-Lv}{2R + Lv} \quad \text{and} \quad \tau' = \frac{2R}{2R + Lv}, \quad \dots \quad (9)$$

the notation being the same as that previously used. Thus the condition for non-reflexion is $R = \infty$, in which case all is transmitted. Hence complete absorption is impossible.

If, therefore, we wish to pass electric waves along wires through any layer of dielectric, or through any other arrangement which affects them, and are desirous of avoiding the annoying disturbance due to return of the transmitted portion

* Oliver Heaviside's 'Electrical Papers,' vol. ii. pp. 141-142.

after reflexion at the end of the line, the following method will suffice.

1. Place at the end of the line a bridge of the form herein described, whose resistance has the value given by the theory for plane waves.

2. Test experimentally the absorbing-power of the bridge, and, if necessary, adjust its resistance until no reflexion can be detected.

University College, Nottingham,
September 1896.

DISCUSSION.

Mr. CAMPBELL asked if the resistances given were expressed in ohms or in electromagnetic units.

Mr. BIDWELL asked if the authors had found that the pencil-trace resistances obeyed Ohm's law. He found that if you balance with one cell in the battery circuit, then, on increasing the battery-power to two cells, the resistance alters.

Mr. APPLEYARD suggested that the variation was caused by the contacts at the ends not being good.

Mr. CAMPBELL said the same variation occurred in the case of mixtures of clay and plumbago where the contacts could be made quite good.

Mr. CARTER suggested electroplating the ends to give good contact.

Mr. BRYAN, in reply, said that in their case they did not require to know the resistance very accurately.