STANDING ELECTRIC WAVES ON PARALLEL WIRES

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Abstract

Measurement of short electric wave-length with a parallel wire receiving system.—Electromagnetic waves of from one to ten meters in length and highly constant in nature were obtained by means of a valve oscillator. Two types of generating circuits are described. Analysis of the possible free modes of electric vibration of the parallel wire receiving system indicates that for normal coupling with the valve generator there are always to be found two sets of current maxima. When the sliding bridge is at a position indicating maximum current flowing through the thermo-junction, standing waves exist in a section of the parallel wires included between the bridge and one or other end of the wire system. A change in the terminal conditions at either end of the parallel wires changes the position of the set of resonance points formed by reflection of waves from that end, but does not alter the location of current maxima which are determined by standing waves reflected from the other end. The half wave-length is equal to the distance between successive positions of the bridge at resonance in each of the two sets. Measurements obtained were constant to one part in one thousand for readings requiring a total time of only from two to four minutes. The measured wave-length is independent of mutual effects of exciter and receiver. It is not altered by a change in the diameter or spacing of the receiving wires, or by a change in the material, provided it is non-magnetic.

THE method of measuring wave-lengths by means of two parallel wires upon which standing electric waves are maintained has been in use for some time. The arrangement of bridged wires is usually spoken of as a Lecher system. In the course of a series of experiments with short waves it became necessary to measure accurately each wave-length in a short time. No method was available for determining with rapidity and precision those positions of the bridge at resonance between which the half wave-length is to be measured. The following note aims to give compete information as to the possible modes of vibration of the simple parallel wire system when used as an isolated receiver of undamped oscillations.

Oscillation Generators

Two very similar triode-valve generating circuits were employed, the essential parts of which are shown in Figs. 1A and 2B. The valve used was a modified form of the Radiatron UV-202 in which the grid connection is fused through the top of the glass tube, so that the usual electrostatic coupling between grid, plate and filament leads is reduced. Nonmetallic sockets were used, and every precaution was taken to secure a minimum of capacity and a symmetrical arrangement in the circuits.

In the first circuit (Fig. 1A), two horizontal brass tubes, 5 mm in diameter, are soldered to the plate and grid leads and are mounted in a vertical plane parallel with each other at a distance apart of 3 cm. Two brass rods fit into these tubes to form a telescoping system, easily variable in length. The condenser *C* consists of two brass plates, each 5 cm square, adjustable as to spacing and as to position along the rods. The plate potential employed is 210 volts, and with normal filament heating the plate current is from 30 to 40 milliamp. When the oscillations start, this current suddenly increases to nearly double its original value. The range of wave-lengths with this set, employing rods and tubes 20 cm in length, is from 100 to 300 cm.

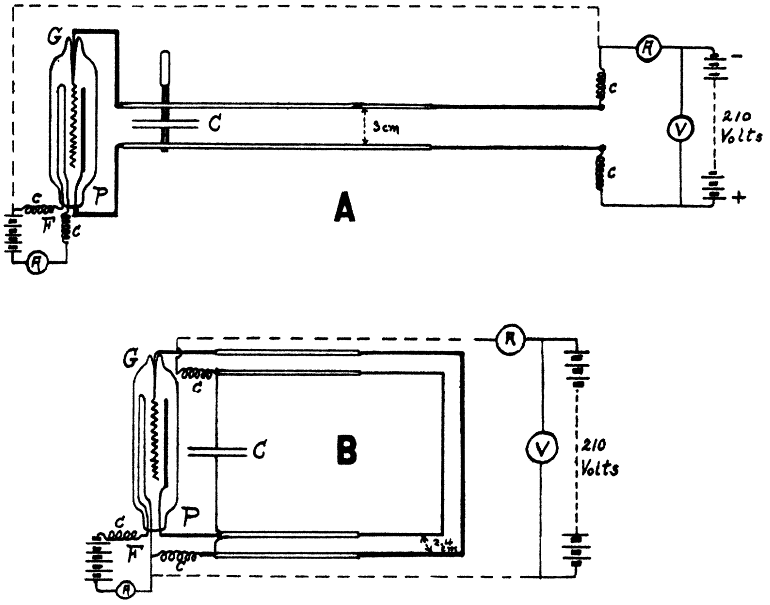

Fig. 1. Generating circuits used.

An alternative generator is shown in Fig. 1B. As in the circuit described above, grid and plate loops consist of tubes and sliding rods. Here the arrangement is more compact, and a condition of stable oscillation more easily secured. This circuit is similar to one employed by Dunmore and Engle[1] for generating waves from 9 to 16 meters in length. The brass condenser plates *C* are 2.4 cm square and are adjustable for spacing but fixed in position. The square shaped loops determine vertical planes,

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[1] Dunmore and Engle, Inst. Radio Eng., Oct. 1923.

which are 2.4 cm apart. The values for plate potential and plate current are as indicated for the first circuit. The range of wave-lengths obtained with this generator is 200 to 1000 cm.

Choke coils, consisting of 20 to 30 turns of No. 18 insulated copper wire wound on soft iron cores .6 cm in diameter, are placed in the circuits at the points marked *c*. These serve to keep the high frequency currents from battery and control leads, and confine them to the oscillatory circuits indicated by the heavier lines in the figures. With careful adjustment the circuits oscillate readily, the wave-length usually remaining constant to within a millimeter. Both generators were mounted on the same control panel and this could be moved to any desired position with reference to the parallel receiving wires.

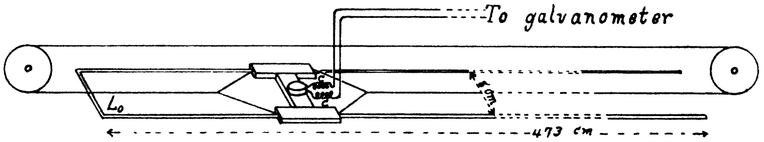

Fig. 2. Parallel wire receiver with sliding bridge.

RECEPTION AND DETECTION OF THE OSCILLATIONS

Two parallel wire systems were employed as receivers. The first was a permanently mounted pair of wires held taut by insulators at a height of 80 cm above one edge of a laboratory table four meters in length. The wires (copper No. 12, B & S gauge) were spaced at 8 cm, and were joined at one end, forming thus a long narrow rectangle with one end open. A bridge was moved along the wires by means of a pulley system as illustrated in Fig. 2.

The thermo-element used to detect the high-frequency current in the resonant circuit was a constantan-manganin couple made with wires .05 mm in diameter, obtained from larger wires by etching them down with acid. The junction used on the permanent system had two such wires each 1 cm long, crossed and soldered at their centers, and mounted in a brass case which was carried on a sliding bridge grooved to follow along the wires. Contact was maintained by terminal leads, one from the constantan end, one from the manganin end, each of which rubbed upon one of the two parallel wires. The other unlike ends of the thermal pair were joined by long leads (Fig. 2) to a Leeds and Northrup galvanometer having a resistance of 26 ohms and a sensitivity of 10^{-9} amp. per scale division.

When the generating circuit was set in operation at a distance of 50 to 150 cm from the parallel receiving wires, slight indications of current could usually be noted on the galvanometer for any position of the bridge. As the bridge was moved along the wires there were certain well defined points at which the thermo-junction current rose suddenly to very high values. These positions of the bridge, or resonance points, could be determined with great accuracy. A slow motion pulley with crank enabled the operator to check each observed position many times. It is with the factors which determine the location of these positions of the bridge at resonance that the present paper is concerned.

Modes of Oscillation of Parallel Wires

Experiment shows that the possible modes of free electrical vibration of an isolated linear conductor are analogous to the possible modes of mechanical vibration of a stretched elastic string. In each case the fundamental or prime mode of vibration is such that the total length of wire or string is approximately equal to the half wave-length of the oscillation associated with the system. In both instances the frequencies of all the free vibrations of a given system bear (nearly) simple integral ratios to each other. In the electrical problem it has been shown conclusively that the wire merely forms a "guide" for the standing electrical waves when the system is vibrating in resonance with an oscillating electrical field, and that the disturbance travels along the wires with the speed of light in air.

Earlier investigators who were concerned with the analysis of the free modes of electrical vibration of parallel wires met with many difficulties. The employment of a spark gap and several closely coupled circuits gave rise to a complicated series of standing waves on the receiving wires. It is not necessary to go into detail concerning these earlier investigations, however, since many undetermined factors have since been eliminated by the use of undamped waves. J. S. Townsend[2] has attacked the problem, using a Lecher wire system coupled to a valve generator by means of a loop. A variable condenser, shunted across the wires near the loop end, served the purpose of so distributing the current maxima that one position of resonance was secured when the bridge was near the free end of wires.

A study of this method of reception indicated that certain maxima were displaced as the capacity of the bridging condenser was changed; but it was also found that certain other maxima were not shifted in position by this manipulation. The distribution of the current along the wires was very irregular, and one could never be quite positive that the

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[2] J. S. Townsend, Phil. Mag. **42**, (1921).

correct successive current maxima had been chosen for the measurement of the half wave. Hours were required to obtain consistent results.

A more rapid and accurate determination of wave-lengths was demanded by the research in progress. A study of the current maxima found by means of a sliding bridge on the simple parallel wire arrangement containing no condenser has revealed a very understandable, rapid and accurate method, and an analysis furnishing a means of rigidly checking results.

In the preliminary tests the permanently mounted pair of wires, closed at one end, were used. The generating circuit was placed at such distances that an amount of energy was transferred to the receiving wires sufficient to give convenient galvanometer deflections. The bridge was moved slowly from one end of the wires to the other, points of maximum deflection being carefully determined by repeated trials.

All current maxima shifted in position for each change in frequency of the exciting oscillations, alternate maxima shifting in opposite directions. All resonance points seemed thus to fall into two groups. If the consecutive bridge positions are numbered from the closed end L_0, Fig. 2, then the *odd* numbered positions L_1, L_3, etc. constitute one group, or set, and the *even* numbered positions L_2, L_4, etc. the other. It was found that $L_3-L_1=L_4-L_2=L_5-L_3$, etc. In one case, for instance, $L_1=93.7$, $L_2=133.7$, $L_3=251.5$, $L_4=291.7$, $L_5=409.4$; hence $L_3-L_1=157.8$, $L_4-L_2=158.0$, $L_5-L_3=157.9$, $L_6-L_4=157.7$. These differences represent the half wave-length of the forced oscillations, the mean error being about .2 per cent.

With the bridge at a point of resonance, a section of the parallel wires including the bridge is vibrating in one of its free modes of oscillation. If the first maximum L_1 shifts to the *left* as the wave-length is increased, then L_2, the second point, will move to the *right*. Evidently each resonance position in the "odd" set indicates the existence of standing waves in that section of the receiver included between the bridge and the "open" ends of the wires. When the bridge is at L_5 the open ends are vibrating in the first free mode; when at L_3, in the second free mode, etc. The same analysis applies to the even numbered positions, with reference here to the bridge and *left*, or closed, end of the receiving wires. When the bridge is at L_2 the closed rectangular circuit at the left is vibrating in its first free mode; when at L_4 the closed loop of length L_4 is vibrating in its second free mode.

The circuit constants which fix the location of these positions of resonance were easily found. The length of wire in the thermo-junction circuit mounted upon the bridge was measured approximately. When this was added to twice the length of the "open" or free ends of the wires measured from the bridge position corresponding to the fundamental vibration in this part of the circuit, the value was always somewhat less than the half wave-length. Evidently the two open ends, joined by means of the bridge, vibrate as a linear oscillator equal in length to $2(L-L_n)+b$, where L is the total length of the parallel wires, L_n the distance measured from the left end of the wires to the *last* "odd" position of the bridge, and b is the length of the bridge wire. In the closed section at the left, for the first free mode of oscillation, it was found in each case that the total length of the circuit was slightly less than the wave-length. The mean value of λ/p, where $p=2(L-L_n)+b$, was found to be 2.095 for a large number of trials employing various wave-lengths. Likewise, the mean value of λ/P, where $P=2L_2+b+e$, and where e represents the wire spacing, is 1.05. These results are shown in Table I.

Results of More Rigorous Experimental Tests

Certain mechanical defects of the system described and used in the tests given above were thought to be the cause of the non-symmetrical variation in the final ratios exhibited in Table I. Among other hindrances was the impossibility of obtaining the equivalent linear dimension of the thermo-junction used. Two additional junctions were made of

Table I

Wave-length and circuit-length ratios in the open and closed ends of parallel wires, for fundamental mode of vibration.

$\lambda/2$	$L-L_n$	L_2	λ/p	$2\lambda/P$
98.0 cm	36.8	83.5	2.16	2.04
123.9	50.4	103.8	2.05	2.14
155.2	65.3	133.2	2.10	2.12
157.9	64.0	133.3	2.17	2.16
158.5	65.9	136.3	2.12	2.14
161.4	68.8	136.4	2.08	2.16
164.6	68.1	140.6	2.15	2.14
167.1	70.5	14[illegible].6	2.12	2.06
167.6	70.0	144.0	2.13	2.12
171.4	74.2	150.0	2.07	2.10
171.8	73.2	148.2	2.09	2.12
176.7	75.0	153.6	2.11	2.12
180.2	79.3	159.2	2.05	2.08
183.5	80.5	159.6	2.06	2.12
222.0	98.8	201.8	2.07	2.06
224.5	98.0	213.0	2.11	2.10
228.4	100.5	221.6	2.10	2.06
258.7	112.8	230.4	2.05	2.04
265.5	121.8	248.3	2.04	2.02
		Mean values	2.095	2.10

L_n = distance to extreme "odd" position of bridge;
L = total length of parallel wires = 473.0 cm;
p = $2(L-L_n)+b$, where b = length of bridge wire;
P = $2L_2+b+e$, where e = spacing between wires.

constantan and manganin wires .05 mm in diameter and 6 mm in length, crossed at their centers and soldered. One such pair mounted in a hard rubber case 2 cm square and 1.2 cm thick, had the advantages of short length and small mass.

An arrangement of receiving wires was built to permit of easy change in dimensions and terminal conditions. This second Lecher system consisted of two parallel wires, each 386.6 cm long, stretched at a distance of 80 cm above the table. Especially designed wire clamps of small mass were supported by hard rubber strain insulators, and these served as "corner" connectors permitting the opening or closing of the ends of the rectangular circuit at will. The strain insulators could be readily adjusted to give any spacing from 2.5 to 50 cm. The dimensions of this system were in each test obtained to within an estimated error of 1 cm for the total perimeter of the circuit.

The complete vindication of this method as a dependable, accurate and rapid means of measuring wave-lengths, demands that the following requirements be adequately fulfilled. (1) The oscillations emitted by the triode generator must be constant and not affected by the presence of neighboring circuits. (2) No complications in resonance conditions may arise on receiving wires for normal coupling with generator. (3) Neither set of current maxima should be displaced when the end conditions determining the other set are altered. (4) Adequate provision must be made for the resolution of current maxima which sometimes occur near together. (5) Variations in the spacing between the parallel wires, and changes in the size or material must not affect the measured wave-length.

A series of tests were made to determine what effect the coupling between the exciter and parallel wires had upon the intensity and position of the two sets of maxima. With the generator at distances of from 50 to 150 cm and approximately parallel to the receiver, both sets of waves were always obtained regardless of the location of the valve circuit along the table, above, below or on either side of the wires. Moreover the wave-length remained constant within the usual error of measurement. The last conclusion is in accordance with the results obtained by Adolf Sheibe,[3] which appeared subsequent to the completion of the present work. In this connection he says, "We can say, therefore, that the undamped electron vibrations are of great constancy, are reproducible, and scarcely to be influenced by outside circuits."

In the further investigation of those characteristics of the receiving wires which determine the positions of the bridge at resonance, two

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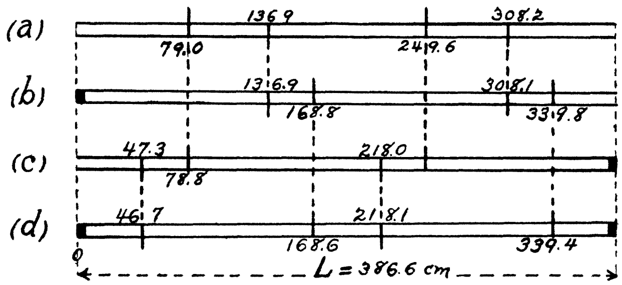
[3] Adolf Sheibe, Ann. der Phy. **73**, No. 54 (1924)

wave-lengths were employed. The diagram of Fig. 3A indicates a typical example of resonance points using a wave-length of 342 cm with wires spaced at 5 cm. A second test of the same circuit using a wave-length of 212 cm confirmed the analysis indicated, no change occurring in one set when the conditions fixing the other set were changed. In arrangement (a) both ends of the parallel wires are open. At a distance of 79.0 cm from the left end the bridge indicates a maximum of current due to a standing wave set up in the left open end. At 249.6 cm another occurs, due to resonance in the section to the left of this position now vibrating in its *second* free mode. These two positions of resonance are also found in arrangement (c) where the left end is open and the right end is closed. Resonance points 308.2 and 136.9 are each due to the open right end oscillating in its first and second free modes, respectively. These positions are found in (b), where the *right* end is still open, *left* end closed. Points 168.8 and 339.8 indicate conditions of resonance in the closed left section of the wires. These positions, and those due to resonance in the closed right end, (47.3 and 218.0, c), both persist in (d) where *both* ends are

A



B

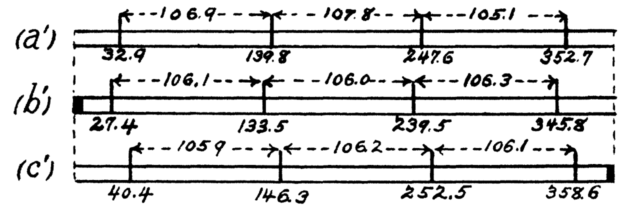


Fig. 3A. Diagram of typical resonance points.
(a) Both ends open; (b) left end closed;
(c) right end closed; (d) both ends closed.
Fig. 3B. Diagram showing overlapping maxima.
(a') Both ends open, maxima formed
by combination of two peaks;
(b') left end closed; (c') right end closed.

closed, and in which no resonance points indicated in (a) are to be found, all terminal conditions being different.

Table II indicates the effect of changing the distance between the wires. The first readings at a spacing of 2.5 cm were taken several weeks after the others, when the generator had been used at various other frequencies. The remainder of the series, beginning with the 5 cm spacing, shows the results of operation with no change in the value of the valve circuit constants. All wave-lengths were measured simultaneously on the permanent receiving system used in the earlier work, and in no case were the average values more than 2 mm at variance with those obtained with the second arrangement.

TABLE II

Showing the effect of changes in the wire spacing.

S	λ	p	P	P/p	P'/p'	$\lambda/2p$	λ/P	$\lambda/2p'$	λ/P'
2.5	206.2	93.4	211.3	2.261		1.103	.977		
	345.6	162.6	350.0		2.152			1.062	.988
5.0	212.2	96.8	217.8	2.250		1.096	.976		
	342.2	162.4	347.2		2.139			1.053	.986
10.0	212.0	97.6	221.0	2.265		1.086	.961		
	341.6	164.0	351.2		2.140			1.042	.973
20.0	212.2	100.8	224.8	2.230		1.057	.944		
	342.8	166.5	355.6		2.137			1.029	.965

P = perimeter of *closed* loop for first free period.
p = total length of *open* end circuit, first free period.
P', p', refer to corresponding circuit lengths for the longer wave-length.
S is the wire spacing.

When the wires were spaced at 20 cm it was found that with both ends of the system open and using the shorter wave, *four* very broad-peaked current maxima occurred where there should have been the usual *eight* sharp resonance points. Moreover the half wave-length as indicated by the distance between those maxima showed more variation than usual. By closing first one end of the parallel wires and then the other, it was found that the broad peaks obtained at first occurred at points approximately midway between the sharp maxima due to wave reflection from each of the open ends. The diagram of Fig. 3B indicates the resolution of current maxima in this case. Those maxima due to reflection from the *closed* ends, as in (a) and (c) of Fig. 3A, have been omitted here.

Copper wires of several diameters were tested with the same wave-lengths, and also aluminum wires of corresponding size. In no case was a change in the measured wave-length observed. Using iron wire, however, satisfactory results were not obtained. The conclusion reached is that the wave-length as measured on the parallel wires is that of the oscillations emitted by the generator, and that no change in wave-length is produced by a change of the diameter of the receiving wires, of the distance between them, or of the material, providing it is non-magnetic and of low resistance.

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