April 16, 1929. S. E. PERO 1,709,037

DISTORTION COMPENSATOR

Filed June 28, 1924 3 Sheets-Sheet 1

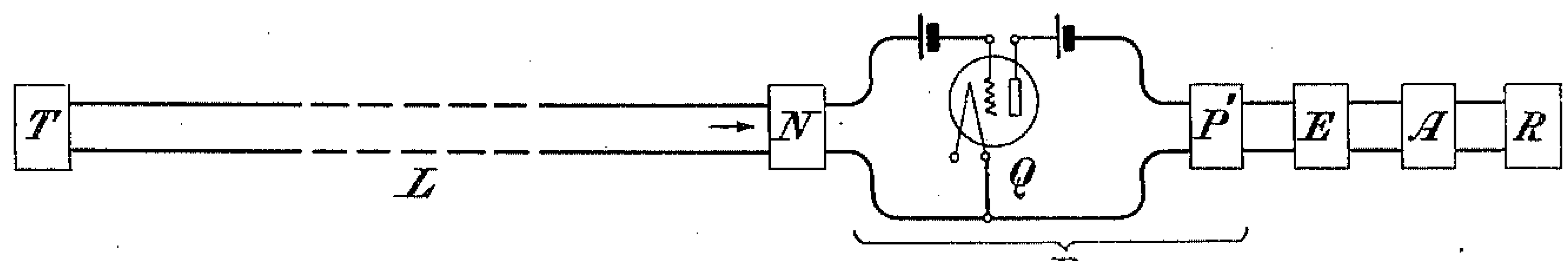

Fig. 1

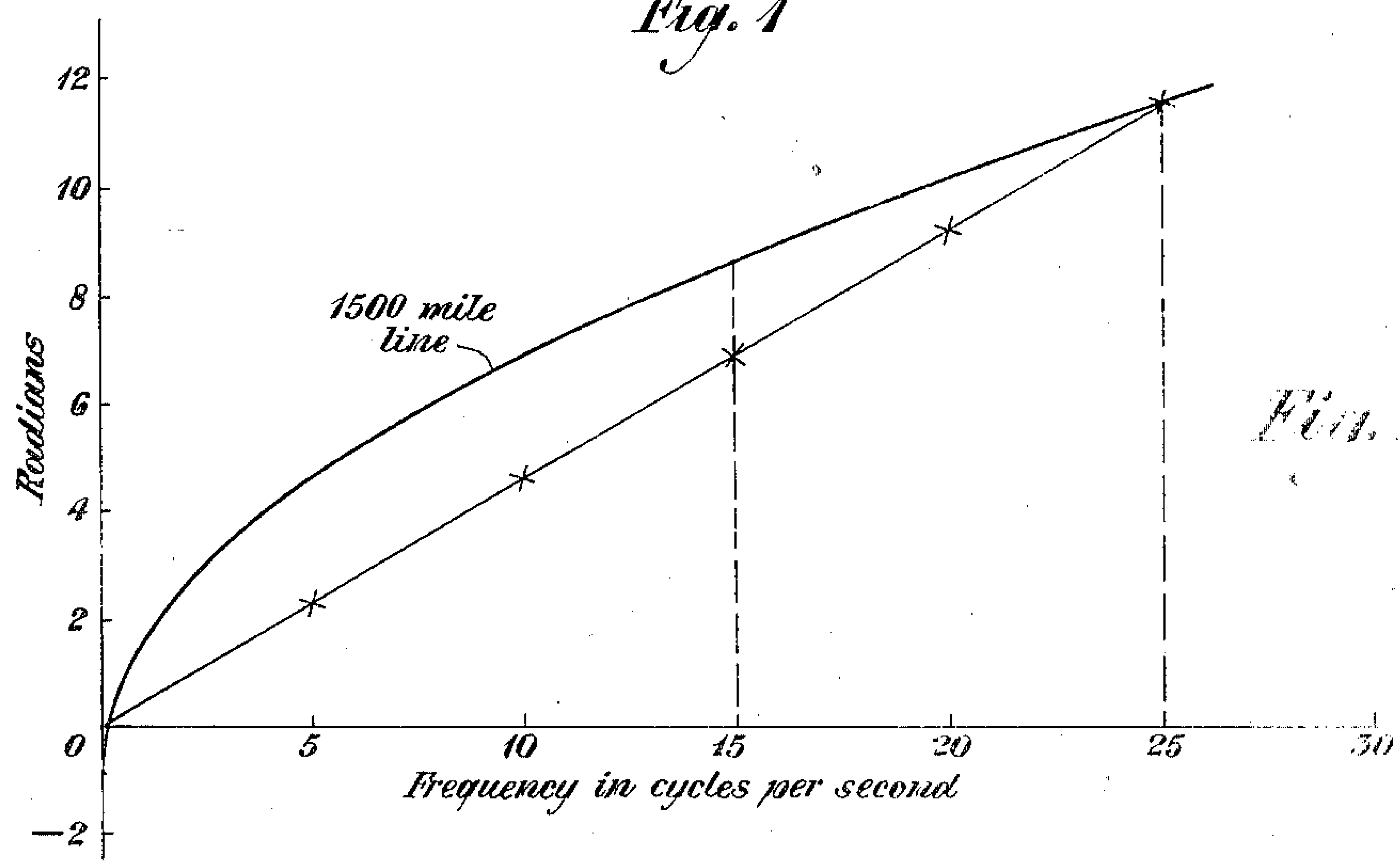

Fig. 2

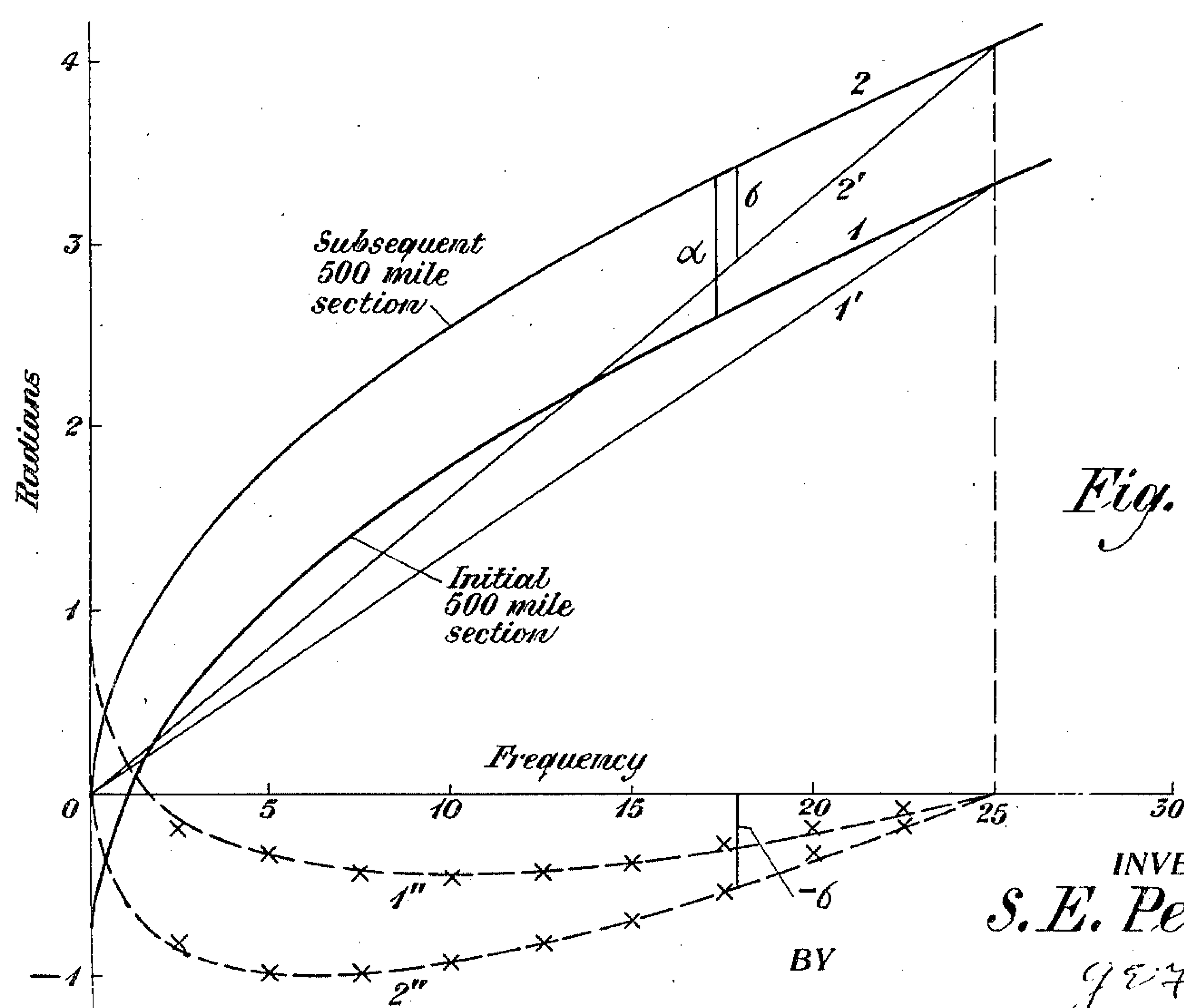

Fig. 3

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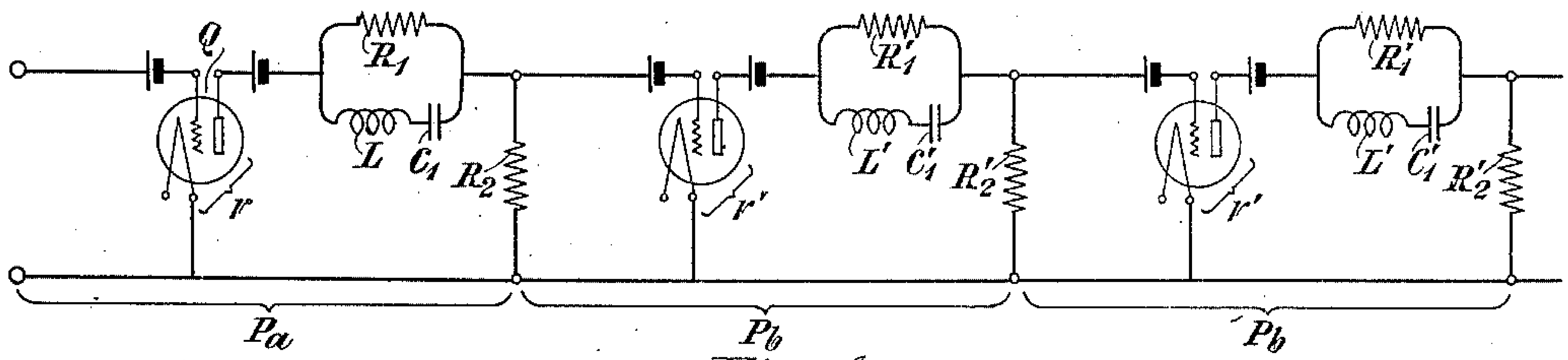

Fig. 4

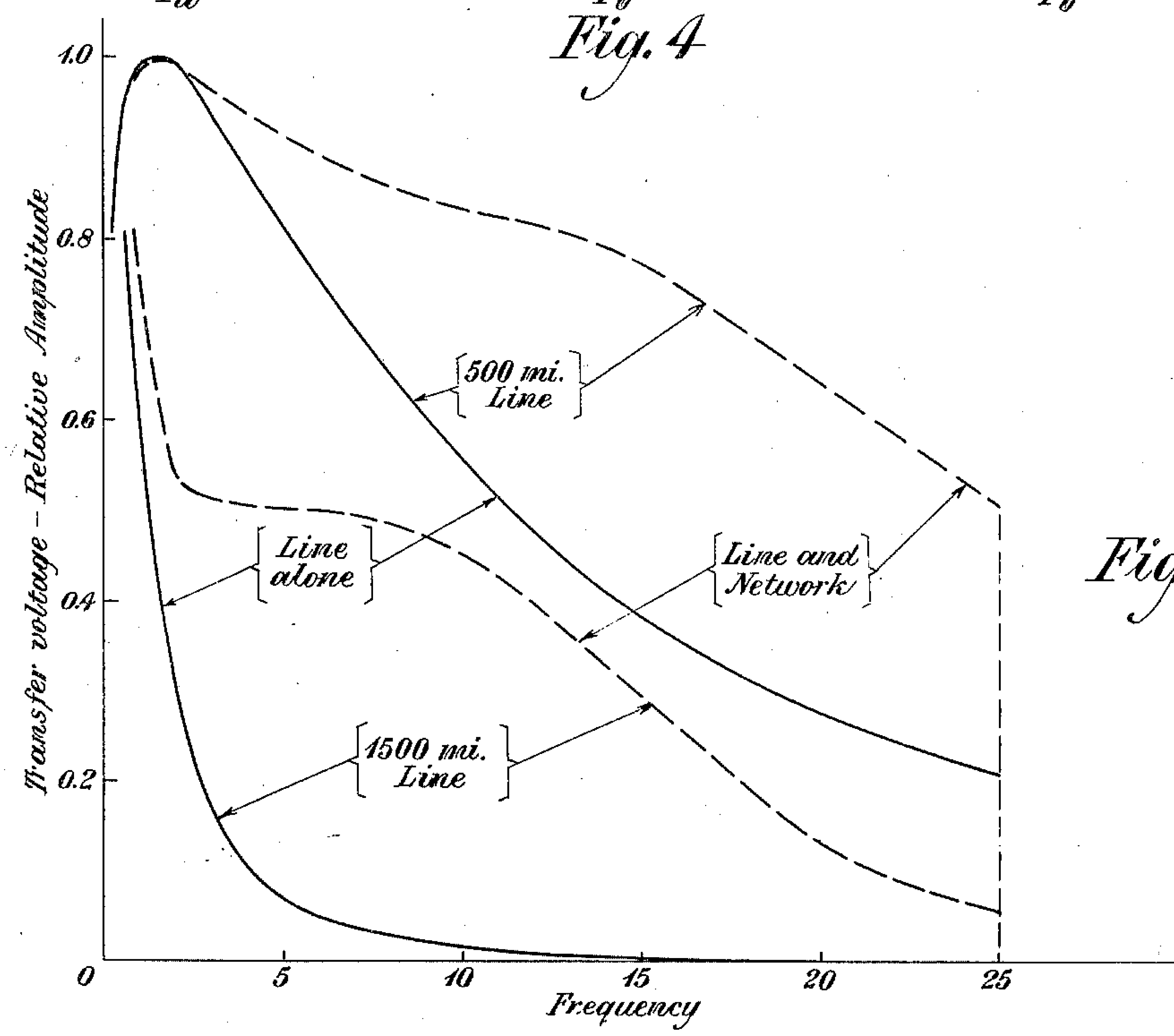

Fig. 5

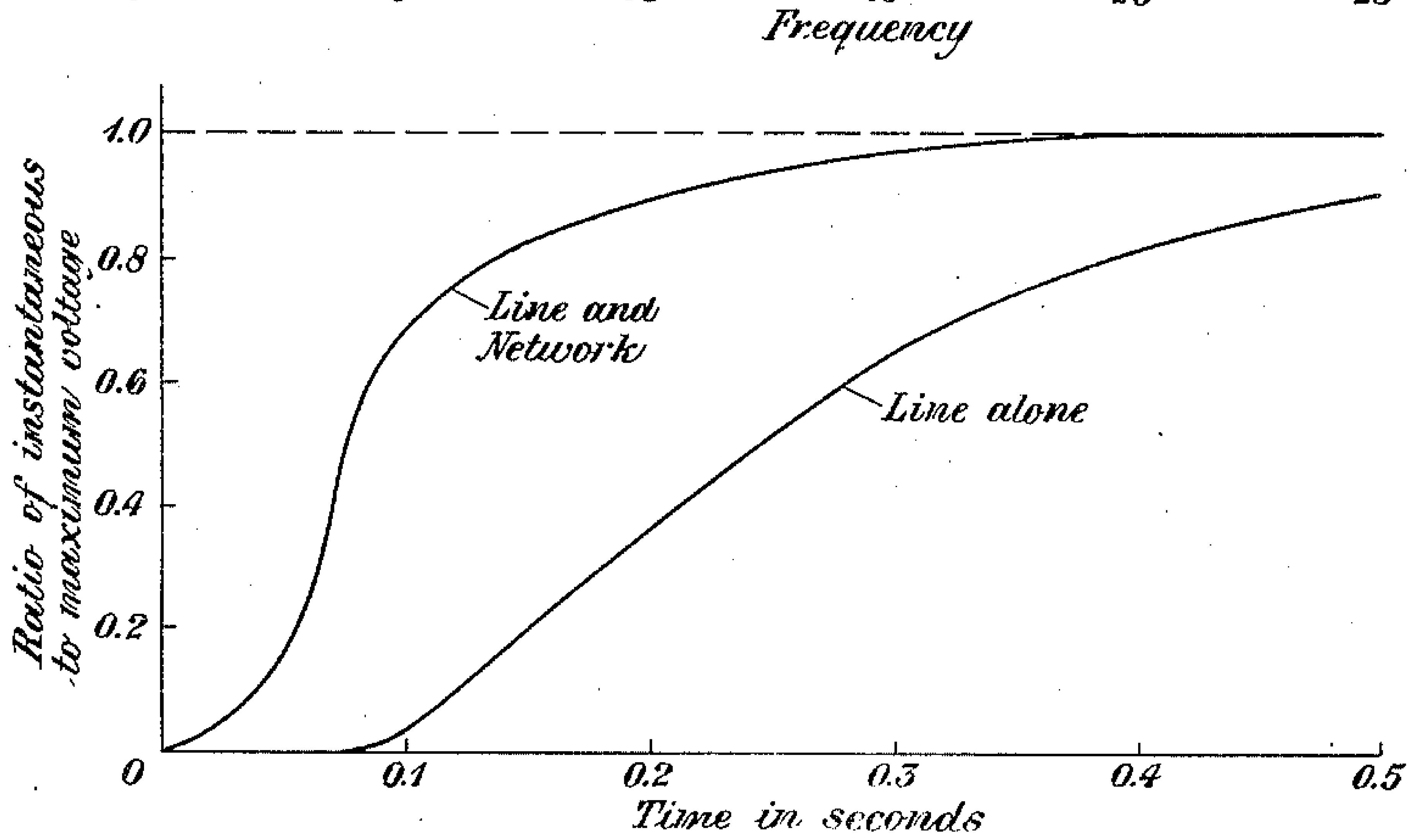

Fig. 6

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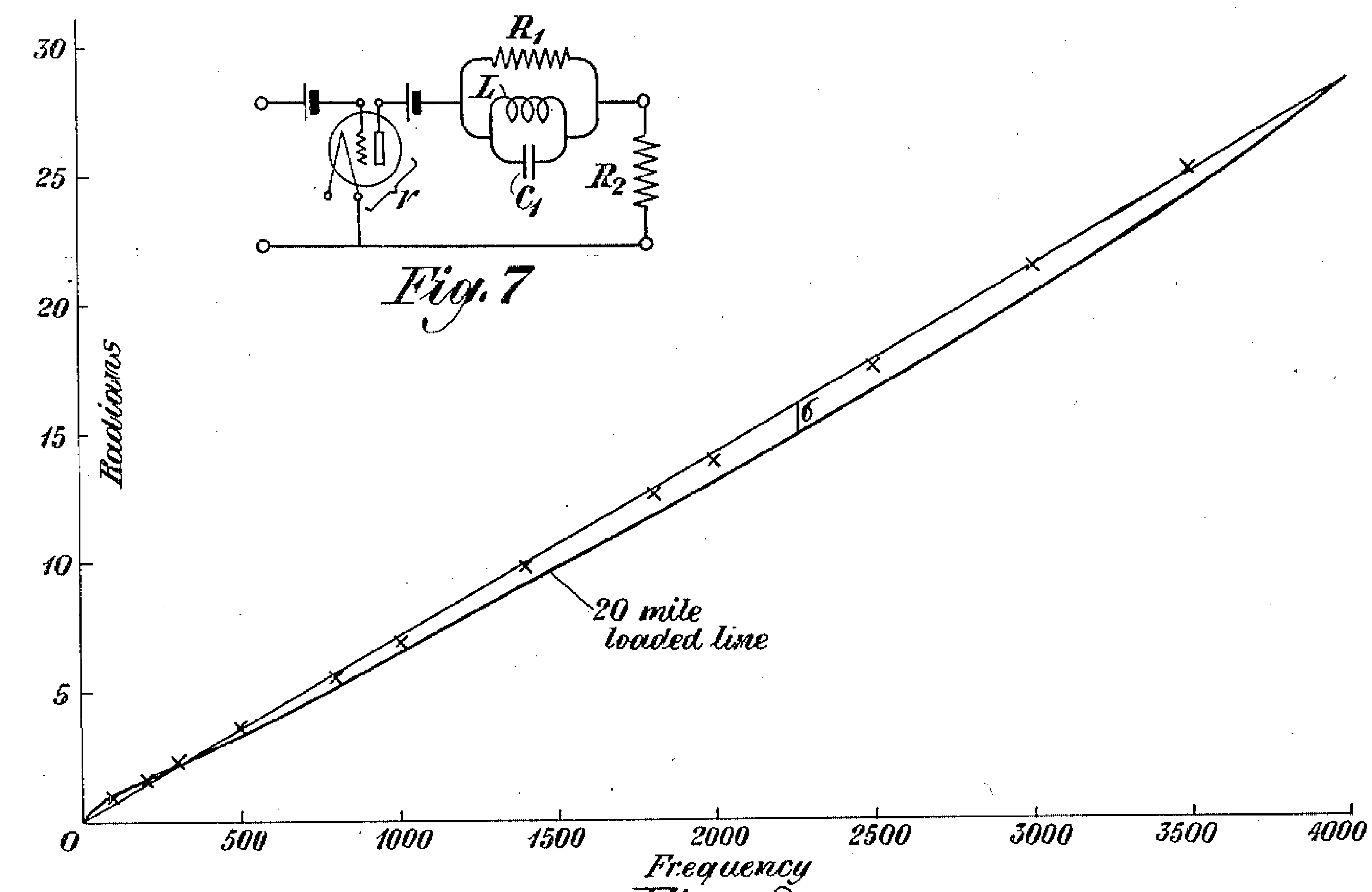

Fig. 7

Fig. 8

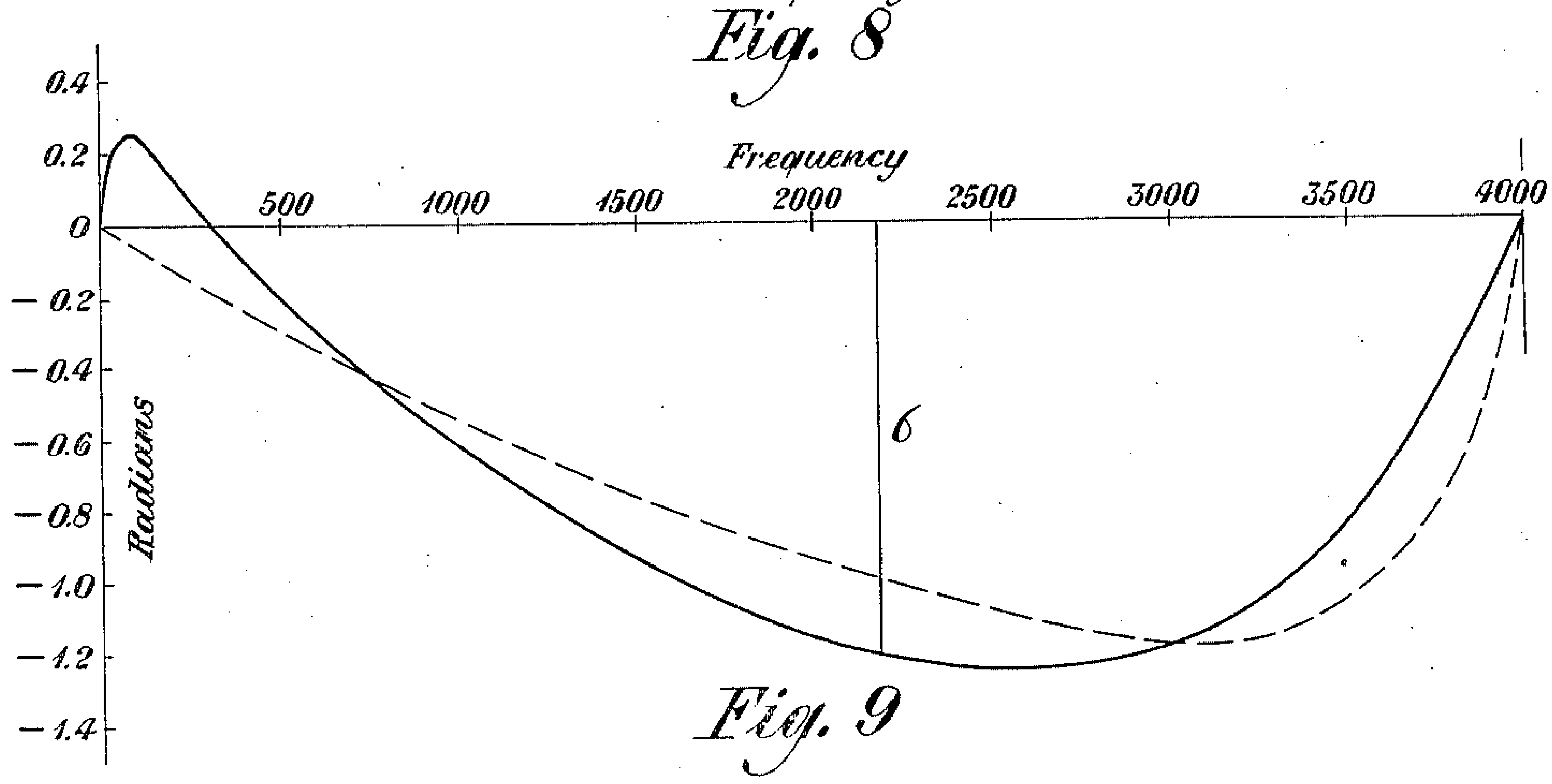

Fig. 9

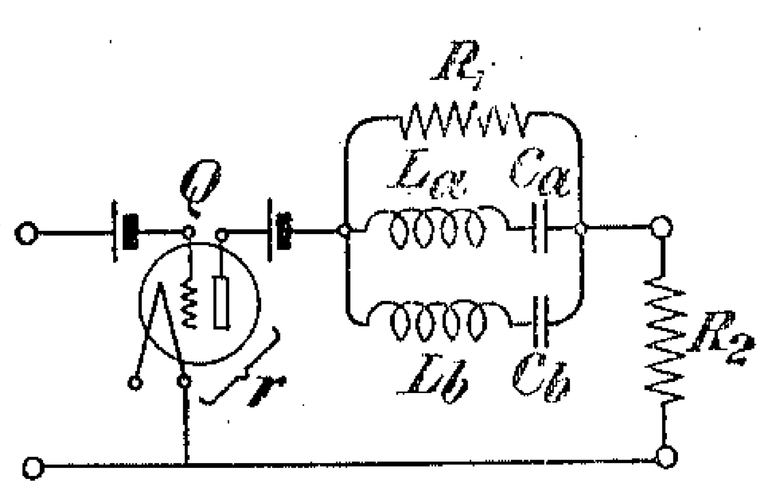

Fig. 10

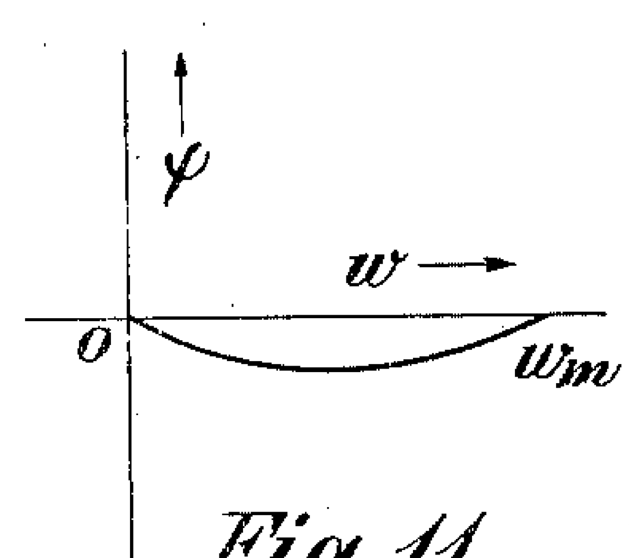

Fig. 11

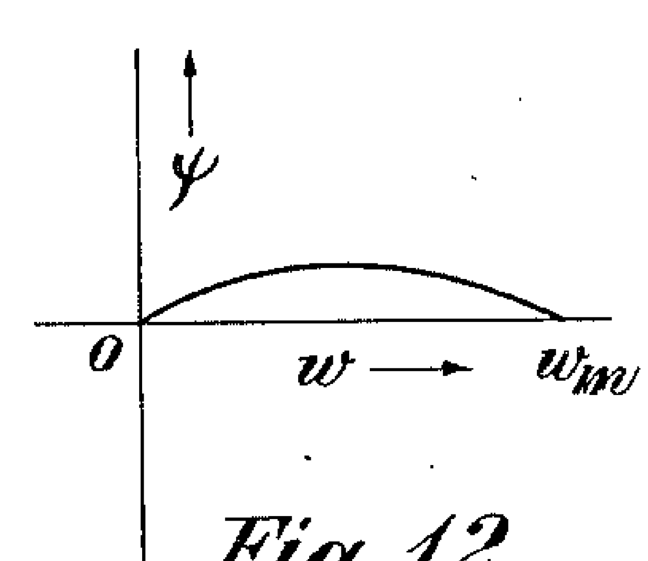

Fig. 12

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Patented Apr. 16, 1929. 1,709,037

UNITED STATES PATENT OFFICE.

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DISTORTION COMPENSATOR.

Application filed June 28, 1924. Serial No. 723,003.

An object of my invention is to provide a new and improved electrical transmission system in which the frequency components of the current within a certain desired frequency range will be in the same phase relation with one another at the receiving end as at the transmitting end. Another object of my invention is to make the received composite wave form in such a system of the same shape as the transmitted wave form. Another object is to provide for a desired displacement in time of the respective frequency components of a composite alternating current. Another object is to provide for a suitable phase shift of currents of different frequencies in a circuit so as to bring them into a desired phase relation. Another object is to provide for a relative phase shift of the frequency components in the output from a transmission line to compensate for the phase shift on the line and to restore the components at the receiving end of the line to the same phase relation as at the sending end. Still another object is to provide a transducer at the receiving end of a transmission line that shall compensate the distortion by differential phase shift on the line. In the following specification, I show several specific examples of practice according to my invention. It will be understood that the specification relates largely to these particular cases and that the invention is defined in the appended claims.

The term "transducer" employed in this specification is meant to refer to any apparatus having a pair of terminals for input electromotive force and another pair of terminals for output electromotive force, the output being a function of the input.

Referring to the drawings, Figure 1 is a symbolic diagram of a system embodying my invention; Fig. 2 is a diagram showing phase displacement on a certain transmission line as a function of frequency; Fig. 3 is a diagram showing phase displacement as a function of frequency for certain sections of the same line and also showing the compensating phase displacements in appropriate networks that are to be combined with the line; Fig. 4 is a diagram showing the network represented by the symbol P in Fig. 1; Fig. 5 is a diagram showing the attenuation in the same line compared with the attenuation in the combined line and network; Fig. 6 is a diagram showing the improvement of the "arrival curve" by the use of my invention; Fig. 7 is a diagram showing a modified network adapted for use in association with a certain loaded line; Fig. 8 is a diagram showing the phase distortion for the loaded line; Fig. 9 is a diagram showing the effect of my improved network in compensating the distortion on this loaded line; Fig. 10 is a diagram for a detail modification; and Figs. 11 and 12 are diagrams that will be referred to in discussing the principles involved in my invention.

Referring to Fig. 1, the line L connects the transmitter T with the receiver R. This line L retards or delays the current components of different frequencies by different amounts, and apparatus is interposed at the receiving end to compensate the differential retardation (as well as the differential attenuation) so that the received wave form shall be the same as at the transmitting end. N is a network whose impedance looking in the direction of the arrow is substantially the same as the characteristic impedance of the line L. The output conductors from the network N are connected in the grid circuit of a three-electrode vacuum tube Q so that practically no current is drawn from the network N but an electromotive force is applied to the grid of the tube Q which is proportional to the current received in the network N.

The output circuit of the vacuum tube Q is connected with the input of the network P′ which is shown in some detail in Fig. 4. As will be explained, its effect is to compensate the phase distortion produced in the line L. The output from the network P (which comprises tube Q and network P′) goes to an attenuation equalizer E; its output goes to an amplifier A, and its output, with the same wave form as at the transmitter T, goes to the receiver R.

As an example with which to illustrate the nature of my invention, let it be assumed that the line L is a submarine cable of length 1,500 miles, whose constants are

resistance $R_0=2.74$ ohms per mile;
inductance $L_0=0.001$ henrys per mile;
capacity $C_0=0.296$ microfarads per mile.

Also let it be assumed that compensation is desired over the frequency range from 2 to 25 cycles per second.

The curve of Fig. 2 gives the angle of retardation or delay for the various frequency components within the range below 25 cycles per second. For example, the component current of frequency 15 cycles per second arrives at the network N in Fig. 1 more than 8 radians behind the input for that component current at the transmitting end of the line L.

The received current would be without distortion if, instead of the curve shown in Fig. 2, its curve were a straight line through the origin. This will be apparent because the phase angle would then be proportional to the frequency, and the absolute retardation of all frequencies would be the same, so that the wave form at the receiving end would be unchanged from that at the transmitting end, so far as distortion due to phase displacement is concerned. To apply my invention as exemplified in the example under discussion, I draw the straight line shown in Fig. 2 to pass through the origin and to intersect the curve at the upper frequency limit, that is, at 25 cycles per second. Then I introduce a compensating network P such that the resultant graph of phase angle against frequency for the combined line and network is given by this straight line.

I make the network P in three sections, each of which compensates for 500 miles of the line. As will be shown presently, the phase shift produced by the initial 500 mile section of the line differs for all frequencies by a certain angle from the phase shift produced by each of the remaining 500 mile sections. This is shown in Fig. 3. The curve 1 gives the phase shift for the initial 500 mile section of the line as a function of frequency and the curve 2 gives the phase shift for each of the remaining 500 mile sections. The ordinates of these two curves at any frequency differ by an angle α. This is the phase angle of the characteristic impedance of the line and its value is

$$\frac{1}{2}\tan^{-1}\frac{R}{WL};$$

it is independent of the length of the line.

The straight line 1′ and 2′ in Fig. 3 are drawn through the origin to intersect the respective curves 1 and 2 at the points corresponding to the limiting frequency 25 cycles. The dotted curve 1″ has negative ordinates each of the same magnitude as the difference between the corresponding ordinates for the curve 1 and the line 1′. Similarly, the curve 2″ corresponds to 2 and 2′.

As shown in Fig. 4, I provide a network of three sections, the first P_a, and the two remaining sections alike, each P_b. The section P_a is intended and designed to have its plot of phase angle against frequency in substantial coincidence with the curve 1″ of Fig. 3, and each of the sections P_b is intended and designed to have its plot of phase angle against frequency substantially coinciding with the curve 2″ in Fig. 3. Accordingly, P_a compensates for the initial 500 mile length of the line L and the two sections P_b compensate for the remaining 1,000 miles of the line L, so that the output of the network P in Fig. 1 has all its components in the same phase relation to each other as at the transmitter end of the line L. This output current from the network P is then passed through the equalizer E, which compensates for differential attenuation to that point, so that the output from E has the same wave form in all respects as the input to the line L at the transmitter T. This output current is amplified at A and received at R.

The nature of the elements of the network of Fig. 4 and their relation to one another are shown clearly in the diagram. The letter r stands for the resistance in the three-electrode vacuum tube Q of its plate circuit. The various resistance and reactance elements in the section P_a and in each section P_b have the values given in the following table:

$$\begin{aligned} r+R_2 &= 5000 \text{ ohms;} \\ R_1 &= 7690 \text{ ohms;} \\ L &= 14.2 \text{ henrys;} \\ C_1 &= 2.85 \text{ mf.;} \\ r'+R'_2 &= 5000 \text{ ohms;} \\ R'_1 &= 51{,}100 \text{ ohms;} \\ L' &= 26.0 \text{ henrys;} \\ C'_1 &= 1.56 \text{ mf.} \end{aligned}$$

The design equations by means of which R_1, L and C_1 of the foregoing values are determined are

$$R_1=\frac{2a(r+R_2)}{\sqrt{a^2+4b}-a}$$

$$L=\frac{a}{w_m}(r+R_2) \qquad (1)$$

$$C_1=\frac{1}{w_m a(r+R_2)}$$

The resistance R_2 should be large enough so there will be a substantial drop through it, but not so large as to impose an inconveniently large value on L in accordance with the second of Equations (1). In the present case, R_2 is chosen to make $r+R_2=5{,}000$ ohms. While the foregoing Equations (1) correspond to the lettering employed for section P_a, they will serve for the sections P_b by adding primes to the letters r, R_1, R_2, L and C_1. In Equations (1) $\frac{w_m}{2\pi}=25$, and in general $\frac{w_m}{2\pi}$ is the upper limiting frequency bounding the range within which distortion is to be compensated. It is at once apparent from Equations (1) that $LC=\frac{1}{w_m^2}$, so that the inductance-capacity combination is resonant at the frequency w_m. a and b of Equations

(1) are determined by the following equations:

$$a=\frac{(x_2^2-x_1^2)\tan\sigma_1\cdot\tan\sigma_2}{x_1x_2(x_1\tan\sigma_1-x_2\tan\sigma_2)}$$
$$b=\frac{x_1\tan\sigma_2-x_2\tan\sigma_1}{x_1x_2(x_1\tan\sigma_1-x_2\tan\sigma_2)} \qquad (2)$$

In general, in Equations (2), σ stands for the part of the ordinate of the corresponding curve 1 or 2 in Fig. 3 above the straight line 1′ or 2′, respectively. Thus σ is the phase angle of distortion lag for the current of corresponding frequency in the section of the line under consideration. σ_1 and σ_2 are values taken at particular frequencies between the lower and upper limits of the range within which compensation is to be effected. The network P_a or P_b has enough undetermined parameters so that its curve 1″ or 2″ of Fig. 3 can be made to intersect the axis of abscissæ at or near zero and at one other point, and in addition to pass through two assigned intermediate points, and σ_1 and σ_2 are the ordinates of the curves 1 or 2, as the case may be, at arbitrarily assigned intermediate frequencies. In the particular example here under consideration, these two intermediate frequencies are 5 cycles per second and 15 cycles per second.

In general, the x's of Equations (2) are given by

$$x=\frac{w}{w_m}\left(1-\frac{w_m^2}{w^2}\right) \qquad (3)$$

where $w=2\pi f$ and f stands for the frequency. w_m has already been explained and defined. The x's of Equations (2) are x_1 and x_2, the particular values given by Equation (3) when f has the particular values already mentioned corresponding to σ_1 and σ_2.

The crosses on or near curves 1″ and 2″ on Fig. 3 show the actual values of phase shift given by the network sections of Fig. 4 and show that the agreement is very close to that desired for perfect compensation as indicated by those curves.

In Fig. 5 the attenuation on the line L as a function of frequency has been indicated by a plot of the transfer voltage ratios; that is at any given frequency the ordinate gives the magnitude ratios of the output voltage to the input voltage. It will be seen that for the full 1,500 mile length, the attenuation is very marked at higher frequencies, so that the transfer voltage has a very low value for the higher frequencies. There is also a very noticeable falling off in the value of this ratio comparing the voltage at the end of the first 500 mile section with the voltage at the input. The dotted lines show the transfer voltages for the combined line and network, both for the full 1,500 mile length of line and for the first 500 mile section. It will be seen that the transfer voltage decreases much less for the higher frequencies for the combined line and network than for the line alone. Accordingly it follows that while my improved network gives approximately complete compensation for phase distortion, it gives substantial partial compensation for attenuation distortion. Referring to Fig. 1, the network P corrects for phase distortion and partially for attenuation distortion, and the attenuation equalizer E completes the correction for attenuation distortion.

In Fig. 6 the "arrival curves" are shown for the 1,500 mile line alone and for the same line combined with the network. It will be seen that my improved network gives an improved arrival curve and thus improves the received signal shape and enables the line to be operated at higher signaling speed.

I have given a specific example of an engineering application of the principle of my invention and have stated the particular design equations that I have found to be applicable for this example. I have also shown the manner of operation of the apparatus embodying the invention in this particular instance. Further to exemplify my invention, I will now show how to equalize for phase distortion in the case of a section of loaded line. Referring to Fig. 1, let it be assumed that the line L is a loaded line 20 miles long, of 19-gauge cable. Let the constants of the 20 mile loaded line be

resistance R_o =81.9 ohms per mile;
inductance L_o =0.001 henry per mile;
capacity C_o =0.062 microfarad per mile;
leakage G_o =$2C_o\times7.8$ micromhos for 900 cycles per second;

inductance of each loading coil =0.0443 henry;
capacity of each loading coil =0.00296 microfarad;
distance between loading coils =1.136 miles.

In this case let it be assumed that compensation is desired over the frequency range from 0 to 4,000 cycles per second.

The curve of Fig. 8 corresponds to that of Fig. 2 for the case of the submarine cable. It will be seen that whereas the angle of distortion σ is positive for Fig. 2, it is negative for most of the range of Fig. 8, that is for the range above a frequency in the neighborhood of 500 cycles per second. In this case compensation can be effected by a single section of network such as shown in Fig. 7, whose elements have the values given in the following table:

$$r+R_2=5{,}000 \text{ ohms};$$
$$R_1=101{,}000 \text{ ohms};$$
$$L=0.46 \text{ henrys};$$
$$C_1=.0216 \text{ microfarads}.$$

The design equations which determine the foregoing values are

$$\begin{aligned} R_1 &= \frac{2a(r+R_2)}{\sqrt{a^2+4b}-a} \\ L &= \frac{a(r+R_2)}{w_m} \\ C_1 &= \frac{1}{w_m a(r+R_2)} \end{aligned} \qquad (4)$$

As before, the resistance R_2 is chosen arbitrarily to make $r+R_2=5{,}000$ ohms. In this case $\frac{w_m}{2\pi}=4{,}000$. It is seen at once from the expressions for L and C_1 that $LC=\frac{1}{w_m^2}$, so that the inductance-capacity combination is anti-resonant at the frequency w_m. a and b are denfied by the following equations:

$$\begin{aligned} a &= \frac{(x_2^2-x_1^2)\tan\sigma_1\cdot\tan\sigma_2}{x_1x_2(x_1\tan\sigma_1-x_2\tan\sigma_2)} \\ b &= \frac{x_1\tan\sigma_2-x_2\tan\sigma_1}{x_1x_2(x_1\tan\sigma_1-x_2\tan\sigma_2)} \end{aligned} \qquad (5)$$

In general x is defined by the equation:

$$x=\frac{w}{w_m}\cdot\frac{1}{1-w^2/w_m^2} \qquad (6)$$

where $\frac{w}{2\pi}$ is the frequency. Two particular values are assigned for w; these are $\frac{w_1}{2\pi}=800$ and $\frac{w_2}{2\pi}=3{,}000$, and the substitution of these values in the foregoing equation gives x_1 and x_2, respectively. σ_1 and σ_2 are the values in Fig. 8 corresponding to the frequencies $\frac{w_1}{2\pi}=800$ and $\frac{w_2}{2\pi}=3{,}000$ respectively.

The crosses on Fig. 8 show the actual values of the phase shift given by the combined 20-mile section of loaded line and the network of Fig. 7. Their proximity to the straight line through the origin shows the high degree of compensation effected by the network when combined with the line.

In Fig. 9, σ is plotted in full lines against frequency with a larger unit for σ. The dotted line plot gives the angle (with sign reversed) due to the network impedance.

If a more accurate approximation is desired than that given by the foregoing procedure, the network sections can be made as shown in Fig. 10 instead of as shown in Fig. 7. This gives more flexibility of design and enables us to fit the curve of the phase angle to the desired curve at two more points than as compared with Fig. 7. Thus referring to Fig. 9, with the design of Fig. 10 the curve (with sign reversed) may be made to go not as shown by the dotted line in Fig. 9, but more as shown by the solid line, that is above the axis at the extreme left and then below the axis.

In the preceding examples of Figs. 4 and 7, letting ψ represent the angle of the transfer impedance of the phase corrector, ψ is given by the equation

$$\psi=\tan^{-1}\frac{ax}{1+bx^2} \qquad (7)$$

where a and b have the values obtained by solving Equations (1) or (4). The phase correctors are designed so that ψ will approximate closely the negative of the angles σ of Figs. 3 and 8. Thus the phase angle ψ of the form represented by Equation (7) may be adapted to correct the phase distortion in various types of networks and transmission lines. a and b are positive constants determined by the arangement of the elements in the corrective network while x is a function of the applied frequency. It may be required that this compensating phase angle given by Equation (7) shall have the value zero when the impressed frequency $\frac{w}{2\pi}$ is zero, and also when it has some other value $\frac{w_m}{2\pi}$, and that the angle be negative in the interval $0<w<w_m$. This corresponds to the case of the submarine cable. With Fig. 11 in view, it will be seen that the angle of Equation (7) satisfies these requirements when $x=\frac{w}{w_m}\left(1-\frac{w_m^2}{w^2}\right)$, for then when $w=0$, $x=-\infty$ and $\psi=0$; when $w=w_m$, $x=0$ and $\psi=0$; and when $0<w<w_m$, $-\infty<x<0$ and $\psi<0$. These conditions are realized in the resonating circuit comprising the elements L and C_1 of Fig. 4 adapted for the example of the submarine cable.

Again, a phase angle may be required which shall be zero for two frequencies, that is, for zero frequency and some other frequency $\frac{w_m}{2\pi}$, but positive in the interval, for example, to be complementary to the distortion on the loaded cable. With Fig. 12 in view for this case put $x=\frac{w}{w_m}/\left(1-\frac{w^2}{w_m^2}\right)$. Then when $w=0$, $x=0$ and $\psi=0$; when $w=w_m$ $x=\infty$ and $\psi=0$; and when $0<w<w_m$, then $0<x<\infty$ and $\psi>0$. These conditions are realized in the circuit given for the loaded cable.

In general, the maximum phase displacement obtainable in a single section is

$$\psi_m = \tan^{-1} \pm \frac{a}{2\sqrt{b}}.$$

Since it is assumed that $b > 0$ and $a < \infty$, it follows that

$$\frac{a}{2\sqrt{b}} < \infty \text{ and } \psi_m < \frac{\pi}{2}.$$

I claim:

1. In combination, a transmission line producing various phase displacements for component currents of various frequencies, and a network of successive sections connected with the line, each section producing phase displacements at the respective frequencies compensating for a corresponding part of the line, whereby the received current has its components in the same phase relation as the transmitted current.

2. In combination, a transmission line producing various phase displacements for component currents of various frequencies, a first network connected therewith having its input impedance the same as the characteristic impedance of the line, and another network comprising a three-electrode vacuum tube having its grid circuit connected with said first network and adapted to produce compensating phase displacements at the respective frequencies in a circuit associated with the plate side of said tube, whereby the current output from the second network has its components in the same phase relation as the transmitted current to the line.

3. A network to compensate phase distortion on a line, said network having a pair of input terminals and a pair of output terminals and comprising a three-electrode vacuum tube with its grid circuit connected to the input terminals and with a pair of parallel branches in the plate circuit, one branch consisting of a resistance and the other branch consisting of inductance and capacity, said plate circuit also having another resistance in series.

4. A network to compensate phase distortion on a line, said network having a pair of input terminals and a pair of output terminals and consisting of a plurality of sections connected in series, each section having a three-electrode vacuum tube with its grid circuit connected to the input end of the section and having two parallel branches in its plate circuit with resistance in one branch and inductance and capacity in the other branch, with the plate circuit completed by a high resistance across the grid circuit terminals of the succeeding section.

5. In combination, a transducer whose plot of phase retardation against frequency between two frequencies is a single valued curve, and in combination therewith a network whose corresponding plot is a complementary curve, so that the sum of the two curves is a straight line through the origin.

6. In combination, a transducer whose plot of phase distortion against frequency is a single valued curve over a desired frequency range from zero to a particular frequency, and in combination therewith a network whose corresponding plot is a complementary curve, so that the sum of the two curves is a straight line through the origin intersecting the first mentioned curve at a point corresponding to the upper limiting frequency of the said range.

7. In combination, a transducer, a network, and an attenuation equalizer, the transducer retarding current components differently and attenuating them differently according to their frequency, the network producing compensating retardations over a desired frequency range, and the attenuation equalizer producing compensating attenuations over the same range, whereby the components in the output from the combination are retarded alike and attenuated alike and have the same phase relation and relative magnitude as the components in the input.

In testimony whereof, I have signed my name to this specification this 26th day of June, 1924.

SALLIE E. PERO.