

June 29, 1948.

K. W. PFLEGER

2,444,063

ELECTRIC CIRCUIT EQUALIZATION

Filed Dec. 7, 1944

3 Sheets-Sheet 1

FIG. 1

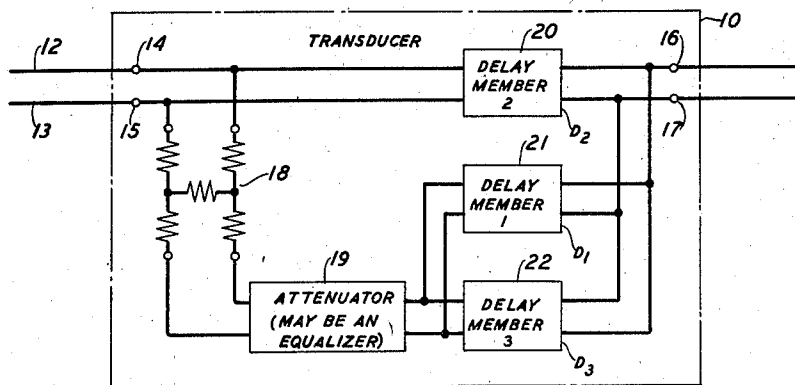


FIG. 2

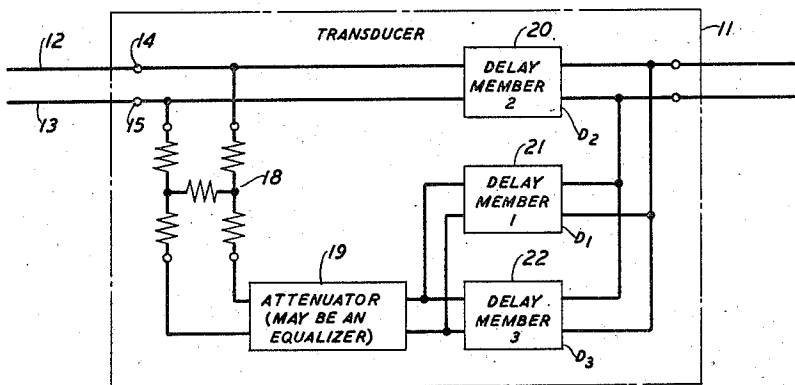
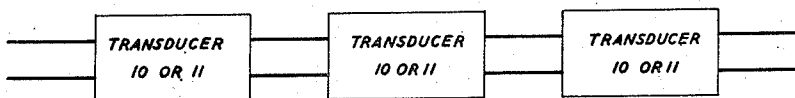


FIG. 3



CORRESPONDING DELAY MEMBERS IN TRANSDUCERS MAY HAVE DIFFERENT DELAYS

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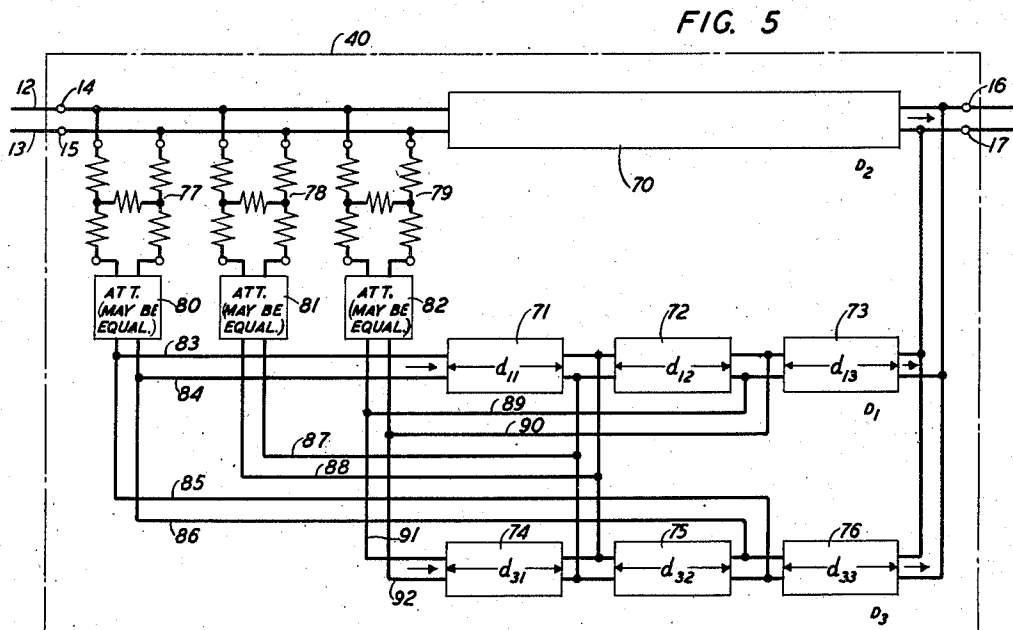
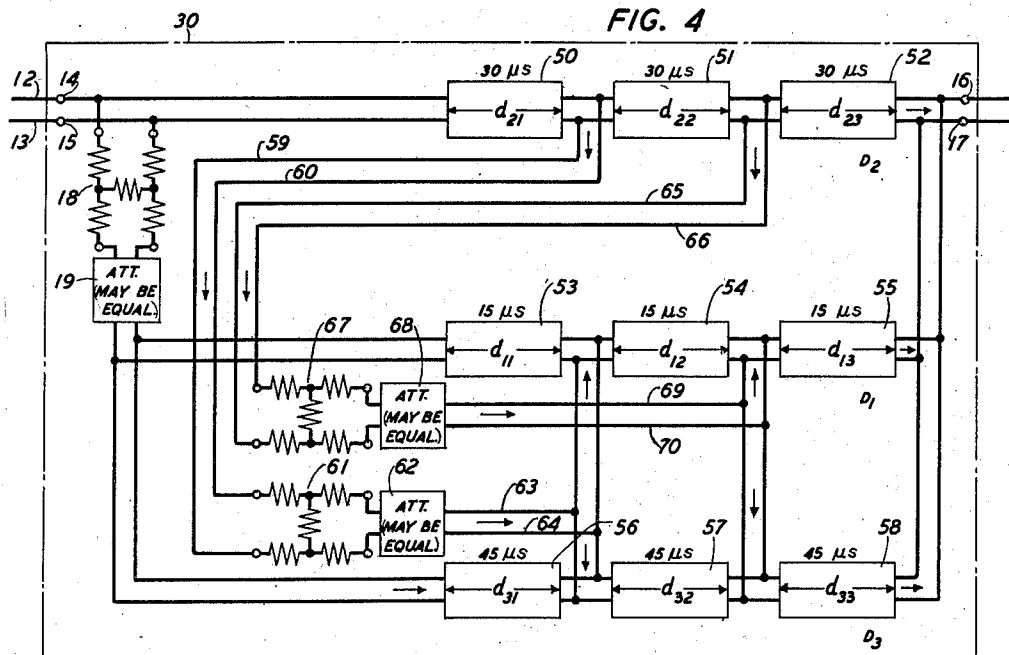
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FIG. 6

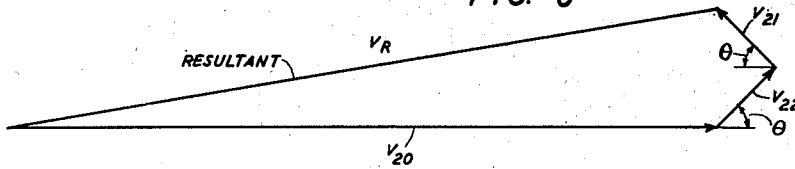


FIG. 7

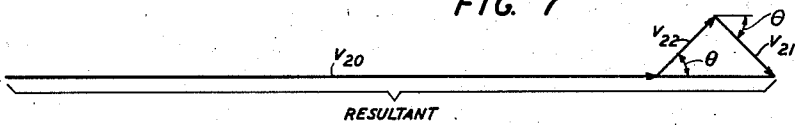


FIG. 8

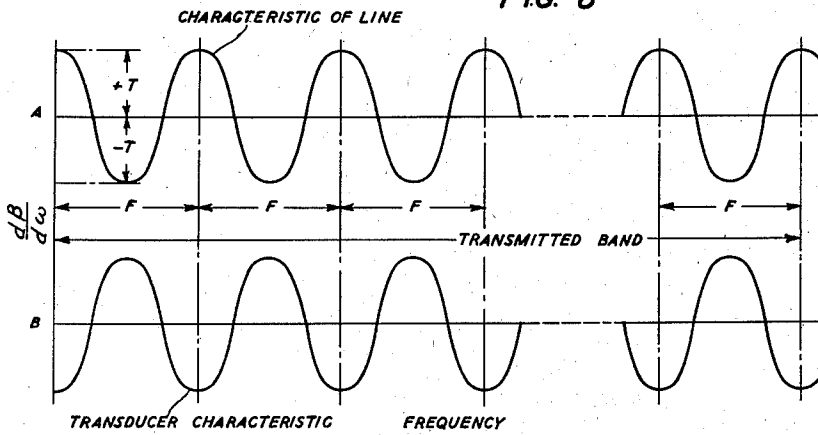
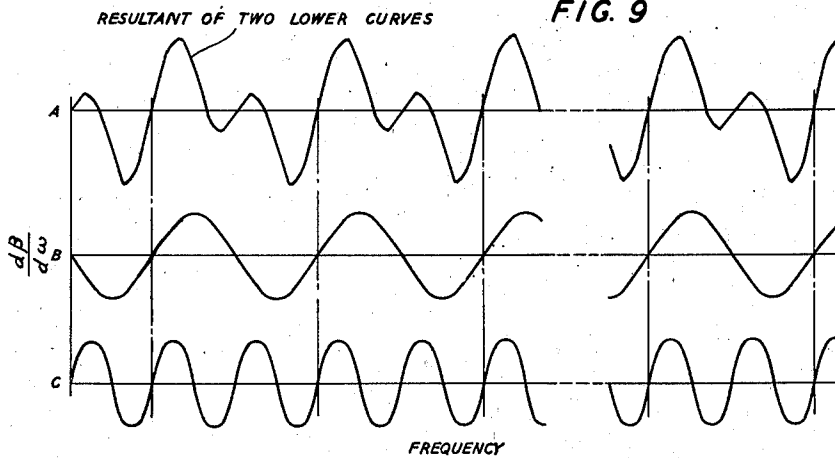


FIG. 9



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UNITED STATES PATENT OFFICE

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ELECTRIC CIRCUIT EQUALIZATION

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9 Claims. (Cl. 178—44)

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This invention relates to electric circuit arrangements and more particularly to the attenuation and envelope delay equalization of waves transmitted over transmission lines.

It is a primary object of this invention to provide novel means for equalizing the attenuation and envelope delay versus frequency characteristics of broad band transmission lines or systems.

Due to the fact that in long wire line signal transmitting systems the line is usually not electrically smooth, that is, electrical impedance irregularities appear at many points along the line, small "wiggles" in the attenuation and envelope delay ($d\beta/d\omega$, where β is the phase retardation and ω is 2π times the frequency in cycles per second) versus frequency characteristics of the system occur. In one of its more important aspects, the invention relates to the removal or reduction of these so-called wiggles.

On a coaxial circuit transmitting a band of from 0.3 to 2.8 megacycles, for example, it is possible that the periodicity of the wiggles will be as low as 0.1 of a megacycle which gives around 25 humps or wiggles in a transmission band 2.5 megacycles wide. The spacing between humps is not necessarily constant over the frequency range, nor are their amplitudes. On long circuits ordinary equalization produces a more nearly flat characteristic but may give rise to an increased number of wiggles and it is possible to design rather complicated mop-up equalizers to equalize these wiggles. In accordance with the present invention, however, compensating wiggles are produced in the attenuation and envelope delay frequency characteristics by means of delayed signals and the apparatus required is very much less than that of a mop-up equalizer which may require many sharply tuned resonant circuits. When the humps or wiggles are spaced at regular intervals along the frequency band and when they are of fairly uniform amplitudes or of amplitudes which vary in a known manner, the saving in apparatus resulting when the present invention is utilized may be very great. The compensating humps or wiggles are produced by combining a pair of properly delayed signals (one delay may be substantially zero if desired) produced in branch circuits with the delayed signal in the main transmission path and, if necessary, by repeating this process any desired number of times.

In a specific form of the invention, chosen by way of example for illustrative purposes, means are provided for diverting at a selected point in the transmission system a portion of the signal and this portion is passed through an attenuator

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and then through two parallel-connected delay networks to produce two delayed signals which are combined with the original signal after it has passed through a third delay network. The phase shifts for any particular frequency of the signal band in the two parallel-connected delay networks are made equal to each other but their phases are respectively of opposite sign with respect to the phase of the signal which is passed through the third delay network, that is, their phases are respectively $+\theta$ and $-\theta$ with respect to that of the wave at the output of the third delay network. The same is true for all frequencies in the band. By means of this arrangement compensating attenuation humps with practically no delay effects are produced, but if the connections from one of the two parallel-connected delay networks are reversed, compensating envelope delay humps can be produced with practically no attenuation effects. If it is desired to produce wiggles of uniform periodicity and varying amplitude, the loss can be varied over the frequency range either by manual or automatic adjustment. If it is desired to produce wiggles of non-uniform periodicity, the delay networks, which in the former cases were of the type to produce uniform envelope delay over the frequency band, can be replaced by delay networks or members which do not produce a flat delay. Where the desired correction is not a simple sinusoidal characteristic with respect to frequency more than one set of delay members can be used in tandem, each with a different amount of delay. By means of a sufficient number of such devices in tandem superimposed sinusoidal components can be obtained to simulate any loss or delay characteristic which is resolvable into a Fourier series.

The invention will be more readily understood by referring to the following description taken in connection with the accompanying drawings forming a part thereof in which:

Fig. 1 is a block diagram of a transmission system employing a transducer in accordance with the invention to reduce regularly recurring humps in the envelope delay versus frequency characteristic of the system;

Fig. 2 is a block diagram of a transmission system employing a transducer to reduce regularly recurring humps in an attenuation versus frequency characteristic of the system;

Fig. 3 is a block diagram of a transmission system employing a plurality of the transducers shown in the systems of Fig. 1 or Fig. 2;

Figs. 4 and 5 are block diagrams of systems em-

playing transducers which are modifications of those shown in Fig. 1; and

Figs. 6 to 9, inclusive, are diagrammatic and graphical representations to aid in the understanding of the invention.

Referring more specifically to the drawings, Fig. 1 shows, by way of example for illustrative purposes and in block diagram form, a transmission system including lines 12, 13 (which may be terminals of a coaxial) and a transducer 10 connected in series with these lines. The transducer has input terminals 14 and 15 and output terminals 16 and 17. The purpose of the transducer 10 is to equalize the transmission system. For example, assume that the envelope delay versus frequency characteristic of the system without the transducer is as shown in line A of Fig. 8 and comprises a number of wiggles of substantially sinusoidal form and of substantially equal amplitude. The purpose of the transducer 10 is to introduce a characteristic such as that shown in line B of Fig. 8 which will compensate for these wiggles and produce a substantially flat characteristic over the transmitted band. This is accomplished by diverting a portion of the energy from lines 12 and 13 through an attenuating pad 18 and through an attenuator 19 which has a constant loss over the entire frequency range. The output energy of the attenuator 19 is divided between a delay member 21 (called delay member No. 1 or D₁) and delay member 22 (called delay member No. 3 or D₃), the output of the delay members 1 and 3 being combined and applied to the lines 12 and 13 in which is inserted a delay member 20 (called delay member No. 2 or D₂). The delay members can be electrical non-dissipative delay networks or cable pairs or radio channels or they can be any other means for producing constant envelope delay regardless of change in frequency. As one example, in each member electric waves may be converted into sound or supersonic waves by means of a crystal or other form of loudspeaker for slower propagation in gases or in liquids and may be reconverted thereafter into electric waves by means of a crystal or other form of microphone. The transmitted frequency band may be shifted to higher frequencies before conversion from electric into supersonic waves and after transmission over the medium may be shifted back again in order to make use of particular speakers or microphones of desirable flat characteristics.

The resultant current at the output of the delay member D₁, D₂ and D₃ is computed below. Assume unit current emerging from D₃, a network or other member having constant loss and envelope delay. To this must also be added currents from D₁ and D₃. Let these currents be of small amplitude r and let their phases be respectively $+\theta$ and $-\theta$ with respect to the phase of unit current from D₂. This condition is obtained by making the losses of D₁ and D₃ equal and by making the total delay of the pad 18, attenuator 19 and the network D₁ less than the delay of D₂ by the same amount, T , as the total delay of the pad, attenuator and network D₃ is greater than the delay of D₂. The combined output is:

$$1 + re^{+i\theta} - re^{-i\theta} \quad (1)$$

where the minus sign of the latter term is due to a reversal of the wires at the output of D₃. Equation 1 may be reduced to:

$$1 + i2r \sin \theta \quad (2)$$

The phase retardation of the resultant, as compared to unit undistorted current is:

$$\beta_1 = -\tan^{-1} 2r \sin \theta = -2r \sin \theta \quad (3)$$

when $2r$ is small.

The envelope delay distortion, that is, the departure from flatness, is:

$$\frac{d\beta_1}{d\omega} = -2r \cos \theta \frac{d\theta}{d\omega} = -2r T \cos \theta \quad (4)$$

where r is the ratio of the current amplitude at the output of D₁ or D₃ to the amplitude at the output of D₂ at a frequency of

$$\frac{\omega}{2\pi}$$

and θ is the phase difference between currents at the outputs of D₁ and D₂ or D₂ and D₃ at such frequency.

Since the desired wiggles have maxima occurring at uniform frequency of F cycles over the frequency range of interest as shown in Fig. 8, line A, it is obvious from Equation 4 that this condition is realized when

$$\frac{d\theta}{d\omega}$$

is constant and θ varies as a straight line function of frequency increasing by 2π radians every time the frequency varies an amount F so that

$$\frac{d\theta}{d\omega} = \frac{1}{F}$$

Accordingly the wiggles expressed by Equation 4 have the amplitude

$$r = 2r \frac{d\theta}{d\omega} = \frac{2r}{F} \quad (5)$$

and therefore

$$r = \frac{1}{2} \tau F \quad (6)$$

If the three delaying transducers D₁, D₂ and D₃ have equal losses, then r denotes the current ratio corresponding to the loss in the pad 18. For example, if the delay humps are two micro-seconds in amplitude and 26,460 cycles apart,

$$r = \frac{1}{2} \times 2 \times 10^{-6} \times 26460 = .02646 \quad (7)$$

which corresponds to a 31.6-decibel pad.

Since envelope delay is defined as the derivative of the phase shift versus ω characteristic, the phase shift may be determined from the delay by integration. Thus the phase shifts corresponding to D₂ and D₃ are respectively.

$$\omega D_2 + \lambda_2 \text{ and } \omega D_3 + \lambda_3$$

where λ_2 and λ_3 are constants of integration. In order to conserve apparatus, let the delay member D₁ and its phase shift be zero. In order to fulfill the requirement given above that the phases of current D₁ and D₃ shall be $+\theta$ and $-\theta$ with respect to the phase of current in the member D₂,

$$+\theta = \omega D_2 + \lambda_2 = \omega D_3 + \lambda_3 - (\omega D_2 + \lambda_2) \quad (8)$$

therefore

$$2\theta = \omega D_3 + \lambda_3 = 2\omega D_2 + 2\lambda_2 \quad (9)$$

and

$$\lambda_3 = 2\lambda_2 \quad (10)$$

Let Equation 8 be differentiated with respect to ω . Then

$$\frac{d\theta}{d\omega} = D_2 = \frac{1}{F} = \frac{1}{26460} = 37.75 \times 10^{-6} \text{ seconds} \quad (11)$$

Similarly from Equation 9:

$$D_3 = \frac{2}{F} = 75.5 \times 10^{-6} \text{ seconds} \quad (12)$$

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Delay members are known which produce envelope delays of these magnitudes.

It is stated above that the required phase shifts are $\omega D_2 + \lambda_2$ and $2\omega D_2 + 2\lambda_2$. λ_2 controls the location of the humps as may be seen when Equation 8 is substituted in Equation 4 giving:

$$\frac{d\beta_1}{d\omega} = -\frac{2r}{F} \cos(\omega D_2 + \lambda_2) \quad (13)$$

Accordingly, λ_2 may be any constant between 0 and 2π depending upon the location of F_1 . When the envelope delay has a minimum at F_1 it is evident from Equation 13 that at this frequency

$$\theta = 2\pi F_1 D_2 + \lambda_2 = 2\pi N \quad (14)$$

where N is any integer.

$$\begin{aligned} \lambda_2 &= 2\pi N - 2\pi F_1 D_2 \\ &= 2\pi(N - F_1 D_2) \end{aligned} \quad (15)$$

Suppose, for example, that $D_2 = 37.75 \times 10^{-6}$ seconds and $F_1 = 300,000$ cycles, then:

$$\begin{aligned} \lambda_2 &= 2\pi(N - 300,000 \times 37.75 \times 10^{-6}) = \\ &= 2\pi(N - 11.325) \end{aligned} \quad (16)$$

In order that λ_2 shall be small it may be desirable to select $N = 11$ so that:

$$\lambda_2 = 2\pi(-.325) = -2.04 \text{ radians or } -117^\circ \quad (17)$$

When λ_2 is other than 0 or 180° it becomes necessary to add a constant phase shift at all frequencies to that of the flat delay medium. Perhaps the simplest way to obtain the desired over-all phase characteristic is to make the path in the delay medium slightly shorter than would be required and then add an electrical network or just a few sections of lattice or bridged-T type phase equalizers in order to make up the difference plus λ_2 . Methods for designing the latter networks are already well known to those skilled in the art of equalizer design and need not be covered here. Thus it is seen that the apparatus required to produce the delay wiggles of line B of Fig. 8 consists of a pad 13 plus two constant delay paths D_2 and D_3 and a few lattice type networks or their equivalent to obtain the desired values for λ_2 and λ_3 .

The amplitude of the resultant current is

$$\sqrt{1 + 4r^2 \sin^2 \theta} = 1 + 2r^2 \sin^2 \theta \quad (18)$$

when r is small.

Since $\log_e(1 + 2r^2) = 2r^2$ when $2r^2$ is small, it follows that the resultant current has amplitude wiggles corresponding to

$$2r^2 = 2(.02646)^2 = .0014 \text{ neper or } .012 \text{ db.} \quad (19)$$

However, the latter are negligible and can probably be tolerated. By suitable design of the delay members, T can be given a suitable frequency characteristic in order to give spacing between humps of $1/T$. The amplitude of the humps can be controlled by the attenuator 19 which alters the value of r over the frequency range. If the attenuator 19 is made an equalizer the hump shown in line B of Fig. 8 can be made to vary over the frequency range rather than all of them being constant as shown in line B of this figure. Thus only four wide band transducers D_1 , D_2 , D_3 and the attenuator 19 can be made to introduce many delay wiggles with amplitude and periodicity varying by suitable amounts over the frequency range with negligible attenuation effects.

Fig. 6 shows vectorially the relation of the voltages V_{20} (the output of the delay member 20), the voltage V_{22} (the voltage of the output of the delay member 22) and the voltage V_{21} (the volt-

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age of the output of the delay member 21). This diagram represents vectorially Equation 1 and it can easily be seen that the resultant voltage V_R for any particular frequency is substantially equal to the voltage V_{20} .

The system shown in Fig. 2 is like that in Fig. 1 except that the connections from the output of delay member No. 1 are reversed with respect to these output connections in the arrangement shown in Fig. 1. The relations of the voltages V_{20} , V_{21} and V_{22} in the transducer 11 of Fig. 2 are as shown in Fig. 7. This diagram shows clearly that the resultant voltage V_R for any particular frequency has an amplitude change but substantially no phase change. The output current at the terminal 16, 17 is:

$$1 + re^{i\theta} + re^{-i\theta} = 1 + 2r \cos \theta \quad (20)$$

There is no delay effect in this case and only attenuation humps result. Therefore this arrangement can be used as an over-all attenuation equalizer with no delay effects. If the attenuation equalizer 19 contained within one or the other of the arrangements of Figs. 1 and 2 does not have constant delay, the over-all output has both delay and amplitude wiggles or humps. It is obvious that omitting delay member D_3 and reducing the delay of D_1 to zero gives rise to a resultant output current for Fig. 1 equal to the expression $1 + r \cos \theta + ir \sin \theta$ which expression has both amplitude and delay wiggles as θ varies with frequency.

Where the desired correction is not a simple sinusoidal characteristic with respect to frequency, more than one device may be used in tandem each with a different value for T . Fig. 3 shows three such devices in tandem each transducer being like that shown in Fig. 1 or Fig. 2. By means of a sufficient number of devices in tandem, superimposed sinusoidal components, such as are shown graphically in Fig. 9 (where the upper curve is the resultant of the two lower curves which are sine waves of different frequencies), may be obtained to simulate any loss or delay characteristic which is resolvable into a Fourier series. It is obvious that where the characteristic is quite irregular the method of utilizing delayed signals may be more expensive than other means on account of the number of delay members in tandem.

When a large number of transducers 10 or 11 are connected in tandem, the amount of apparatus in the delay networks or other delay members may become excessive. Figs. 4 and 5 disclose arrangements wherein some of the delay members do multiple duty, thus saving a considerable quantity of delay networks.

In the arrangement of Fig. 4 the transducer 30 includes three paths D_1 , D_2 and D_3 as before but each of these paths includes three delay members. The upper path D_2 includes the three delay members 50 (having a delay d_{21}), 51 (having a delay d_{22}), and 52 (having a delay d_{23}). The middle path D_1 includes the delay members 53 (delay d_{11}), 54 (delay d_{12}), and 55 (delay d_{13}) while the lower path D_3 includes the delay members 56 (delay d_{31}), 57 (delay d_{32}), and 58 (delay d_{33}). Signals from the lines 12, 13 are applied to the delay member 50 and the output thereof is applied to the delay member 51 and also, by means of lines 59 and 60, to an attenuating pad 61 the output of which is applied through an attenuator 62 to conductors 63 and 64 which are connected to the input terminals of the delay member 54 in the path D_1 and to the input termi-

nals of the delay member 57 in the path D₃. The output terminals of the delay member 51 are connected to the input terminals of the member 52 and by means of lines 65 and 66 to an attenuating pad 67 the output of which is applied through attenuator 68 to the lines 69 and 70 which are connected to the input terminals of the delay member 55 in the path D₁ and to the input terminals of the member 58 in the path D₃. The signals from the lines 12 and 13 are also applied through attenuating pad 18 and attenuator 19 to the input terminals of both the members 53 and 56, the output terminals of which are connected respectively to the input terminals of the delay members 54 and 57. In turn, the output terminals of the members 54 and 57 respectively are connected to the input terminals of the members 55 and 58. The output terminals of the delay members 55 and 58 are connected to the output terminals 16, 17 of the transducer 30 to which output terminals are also applied the output signals from the delay member 52 in the path D₂. By way of example, each of the members 50, 51 and 52 may have a delay (d_{21} , d_{22} or d_{23}) of 30 microseconds, each member 53, 54 and 55 may have a delay (d_{11} , d_{12} or d_{13}) of 15 microseconds while each of the members 56, 57 and 58 may have a delay (d_{31} , d_{32} or d_{33}) equal to 45 microseconds. (In other examples, each delay member in a path need not equal the other delay members in the path.) Then

Delay $D_2 = d_{21} + d_{22} + d_{23} = 90$ microseconds,
 Delay $D_1 = d_{11} + d_{12} + d_{13} = 45$ microseconds, and
 Delay $D_3 = d_{31} + d_{32} + d_{33} = 135$ microseconds.

With this arrangement delayed signals from 45 microseconds to 135 microseconds in 15-microsecond steps can be obtained and these are all applied to the output terminals 16, 17. To obtain a delay of 45 microseconds the signal travels through the delay members d_{11} , d_{12} and d_{13} . To obtain a delay of 60 microseconds the signal travels through the delay members d_{21} , d_{12} and d_{13} . The 75-microsecond delay is obtained by the signal passing through the delay members d_{21} , d_{22} and d_{13} in tandem. A 90-microsecond delay is obtained by the signal passing through the delay members d_{21} , d_{22} and d_{23} . A delayed signal 105 microseconds behind the input signal is obtained by the signal passing through delay members d_{21} , d_{22} and d_{33} . A 120-microsecond delay is produced by the signal traversing in turn the delay members d_{21} , d_{32} and d_{33} . The 135-microsecond delay is produced by the signal passing in turn through the delay members d_{31} , d_{32} and d_{33} . All of these figures neglect the delays of the pads and attenuation equalizers which are small compared with the delays produced by the delay members. It will be seen that if 90 microseconds is considered to be the mean delay, these delay times can be arranged in three groups, viz., 75, 90 and 105; 45, 90 and 135; and 120, 90 and 60. In each group the difference between the smaller delay and the mean delay is equal to the difference between the mean delay and the larger delay. Thus three sets of wiggles are produced to compensate corresponding wiggles in the input signal characteristic. The delay members may be non-dissipative networks or cable pairs or radio channels or acoustic members or any other suitable means. The delay in the path D₁ can be zero, if desired. It should be understood that power flows in Fig. 4 only in the directions shown by the arrows and that one-way devices (not shown) such as hybrid coils or amplifiers are provided to

prevent power flow in directions contrary to the arrows.

An alternative arrangement to that of Fig. 4 is shown in Fig. 5. In the arrangement of Fig. 5 the path D₂ of the transducer 40 comprises a single large delay member 70 and the path D₁ comprises the three smaller delay members 71, 72 and 73 (they may be equal or unequal) in tandem, these members giving the delays d_{11} , d_{12} and d_{13} , respectively. The path D₃ contains the delay members 74, 75 and 76 (which may be equal or unequal) having delays of d_{31} , d_{32} and d_{33} , respectively. Signals from the input terminals 14, 15 are applied through the attenuating pads 77, 78 and 79, respectively, to the attenuators 80, 81 and 82, respectively. The attenuator 80 is connected to the delay member 71 by means of the conductors 83 and 84 and is connected to the delay member 76 by means of the conductors 85 and 86. The attenuator 81 is connected by means of the conductors 87 and 88 to the input terminals of the members 72 and 75 while the attenuator 82 is connected by means of the conductors 89 and 90 to the input terminals of the member 73 and by means of the conductors 91 and 92 to the input terminals of the delay member 74. The output terminals of the members D₂, 73 and 76 are connected to the output terminals 16, 17 of the transducer 40. These output terminals in Fig. 5 are connected to produce regularly recurring humps in the attenuation versus frequency characteristic of the system while the arrangement of Fig. 4 is connected to produce regularly recurring humps in the envelope delay versus frequency characteristic of the system but it is to be understood that either of the transducers 30 and 40 can be readily adapted by proper connections of these output terminals to produce humps in either of the envelope delay or attenuation characteristics. In the arrangement of Fig. 5, one large delay member 70 is used instead of the three delay members 50, 51 and 52 in the transducer 30 in Fig. 4 but in the arrangement shown in Fig. 5 a finite delay is required in the path D₁ which in the arrangement of Figs. 1, 2 and 4 can be zero. In the arrangement of Fig. 5, wiggles are produced having crests far apart using delays so that the delay in the path D₂ minus the delay in the path D₁ equals the delay in the member 76 minus the delay in the path D₂. Similarly, there are produced wiggles having crests close together by proportioning the delays so that the delay in the path D₂ minus the delay in the members 72 and 73 equals the delay in the members 75 and 76 minus the delay in the path D₂. This positive delay is greater than the positive delay produced in the path D₂ minus that produced in the path D₁. There are also produced wiggles having crests still closer together by proportioning the delays so that that produced in the path D₂ minus that produced in the member 73 equals the delay produced in the path D₃ minus that produced in the path D₂. This is a positive delay much greater than that produced in the paths D₂ minus that produced in the path D₁. Since the delay in the path D₁ equals $d_{11} + d_{12} + d_{13}$ and the delay in the path D₃ equals $d_{33} + d_{32} + d_{31}$, it follows that d_{11} equals d_{32} and d_{12} equals d_{31} .

Although the present invention has been described in terms of certain illustrative embodiments it should be realized that the invention has several features susceptible of embodiment in a wide variety of other forms, and the invention is to be understood as comprehending such other

forms as may fairly come within the spirit and letter of the appended claims.

What is claimed is:

1. In a signal transmission system, the method of reducing substantially regularly recurring humps in a transmission characteristic of the system which varies with frequency which comprises diverting a portion of the main signal through two branch paths and passing the main signal through a third path, the transmission characteristics of the three paths being such that the phases of any sinusoidal component of the resultant signal in one of the two branch paths and of the same sinusoidal component of the resultant signal in the other of the two branch paths are respectively $+\theta$ and $-\theta$ with respect to the phase of the same sinusoidal component of the signal in the third path, where θ is any convenient phase difference, and combining the output signals of the three paths to form a composite signal.

2. In a signal transmission system, the method of reducing substantially regularly recurring humps in an envelope delay versus frequency characteristic of the system which comprises diverting a portion of the main signal through two branch paths and passing the main signals through a third path, the transmission characteristics of the three paths being such that the phases of any sinusoidal component of the resultant signal in one of the two branch paths and of the same sinusoidal component of the resultant signal in the other of the two branch paths are respectively $+\theta$ and $-\theta$ with respect to the phase of the same sinusoidal component of the signal in the third path, where θ is any convenient phase difference, and combining the output signals of the three paths to form a composite signal.

3. In a signal transmission system, the method of reducing substantially regularly recurring humps in attenuation versus frequency characteristic of the system which comprises diverting a portion of the main signal through two branch paths and passing the main signals through a third path, the transmission characteristics of the three paths being such that the phases of any sinusoidal component of the resultant signal in one of the two branch paths and of the same sinusoidal component of the resultant signal in the other of the two branch paths are respectively $+\theta$ and $-\theta$ with respect to the phase of the same sinusoidal component of the signal in the third path, where θ is any convenient phase difference, and combining the output signals of the three paths to form a composite signal.

4. The method of claim 1 in further combination with the step of repeating this method with the output signal produced thereby but utilizing paths having transmission characteristics so that θ has a different value than before.

5. In combination, a signal path having impedance irregularities which produce a multiplicity of small humps in a transmission characteristic of the path which varies with frequency and a transducer connected in said signal path for reducing certain ones, at least, of said humps, said transducer comprising means for diverting a portion of the transducer input signal through two branch paths, means for passing another portion of this input signal through a third path including a delay member, the transmission characteristics of said three paths being such that output signals are produced having for any particular sinusoidal component phases which are respectively $+\theta$ and $-\theta$ with respect to the same

sinusoidal component of the signal produced in said third path, where θ is any convenient phase difference, and means for combining the output signals of said three paths.

6. In combination, a signal path having impedance irregularities which produce a multiplicity of small humps in the envelope delay versus frequency characteristic of said path and a transducer connected in said signal path for reducing certain ones, at least, of said humps, said transducer comprising means for diverting a portion of the transducer input signal through two branch paths, means for passing another portion of this input signal through a third path including a delay member, the transmission characteristics of said three paths being such that output signals are produced having for any particular sinusoidal component phases which are respectively $+\theta$ and $-\theta$ with respect to the same sinusoidal component of the signal produced in said third path, where θ is any convenient phase difference, and means for combining the output signals of said three paths according to the formula $1+re^{+i\theta}-re^{-i\theta}$, where r is the magnitude of the current in each of the two branch paths referred to the magnitude of the output signal in said third path as unity.

7. In combination, a signal path having impedance irregularities which produce a multiplicity of small humps in the attenuation versus frequency characteristic of said path and a transducer connected in said signal path for reducing certain ones, at least, of said humps, said transducer comprising means for diverting a portion of the transducer input signal through two branch paths, means for passing another portion of this input signal through a third path including a delay member, the transmission characteristics of said three paths being such that output signals are produced having for any particular sinusoidal component phases which are respectively $+\theta$ and $-\theta$ with respect to the same sinusoidal component of the signal produced in said third path, where θ is any convenient phase difference, and means for combining the output signals of said three paths according to the formula

$$1+re^{+i\theta}+re^{-i\theta}$$

where r is the magnitude of the current in each of the branch paths referred to the magnitude of the output signal in said third path as unity.

8. In combination, a signal path having impedance irregularities which produce a multiplicity of small humps in a transmission characteristic of the path which varies with frequency and a transducer connected in said signal path for reducing certain ones, at least, of said humps, said transducer comprising means for diverting a portion of the transducer input signal through two branch paths, means for passing another portion of this input signal through a third path including a delay member, the transmission characteristics of said three paths being such that output signals are produced having for any particular sinusoidal component phases which are respectively $+\theta$ and $-\theta$ with respect to the same sinusoidal component of the signal produced in said third path, where θ is any convenient phase difference, means for combining the output signals of said three paths, each of said three paths comprising a plurality of delay members in tandem, and means for passing portions of the signal in said third path, delayed to extents which are less than that of the total delay of said path,

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to points in said two branch paths intermediate the ends thereof.

9. In combination, a signal path having impedance irregularities which produce a multiplicity of small humps in a transmission characteristic of the path which varies with frequency and a transducer connected in said signal path for reducing certain ones, at least, of said humps, said transducer comprising means for diverting a portion of the transducer input signal through two branch paths, means for passing another portion of this input signal through a third path including a delay member, the transmission characteristics of said three paths being such that output signals are produced having for any particular sinusoidal component phases which are respectively $+\theta$ and $-\theta$ with respect to the same sinusoidal component of the signal produced in said third path, where θ is any convenient phase

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difference, means for combining the output signals of said three paths, each of said two branch paths comprising a plurality of delay members in tandem, and means for diverting portions of said input signal in each case through one or more of the members in one of said branch paths and, in addition, through one or more of the members in another of said paths.

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