Nov. 9, 1954 P. W. ROUNDS 2,694,184

EQUALIZER

Filed March 16, 1951

FIG. 1

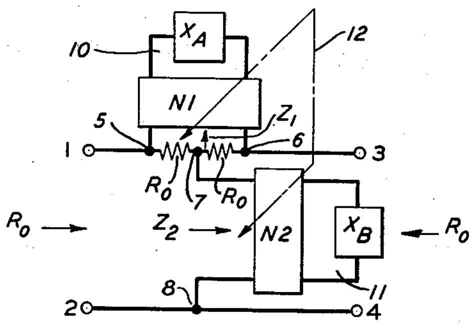


FIG. 2

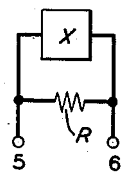


FIG. 3

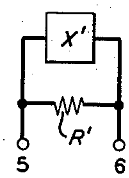


FIG. 4

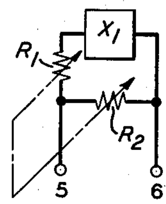
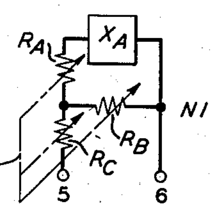
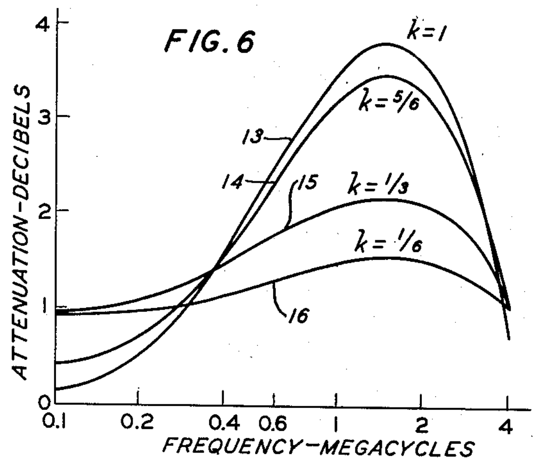
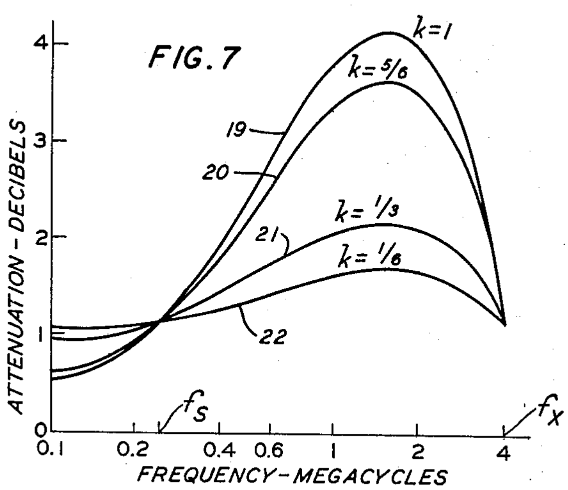
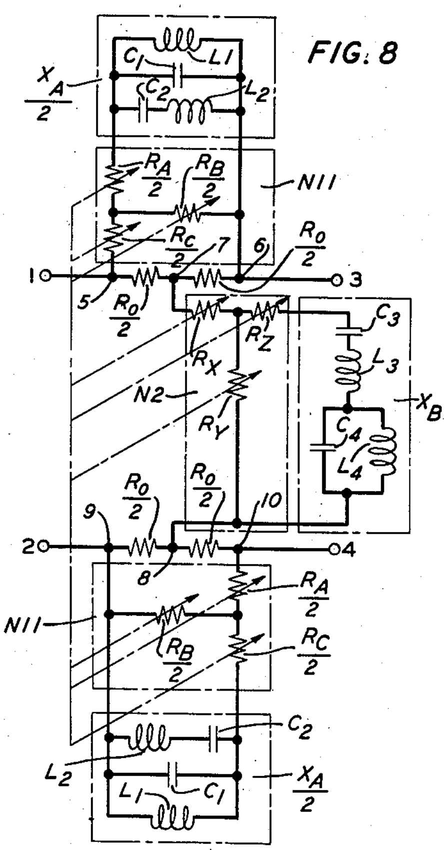


FIG. 5









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EQUALIZER

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5 Claims. (Cl. 333—28)

This invention relates to wave transmission networks and more particularly to adjustable equalizers.

An object of the invention is to select a desired proportional part of the discrimination characteristic of an equalizer and at the same time adjust the attenuation level as desired. A further object is to keep the attenuation substantially constant at an arbitrarily chosen frequency as the equalizer characteristic is adjusted.

In one embodiment the equalizer in accordance with the present invention is a bridged-T structure comprising two series resistors which are ordinarily equal, an interposed shunt branch and a bridging branch. The bridging branch and the shunt branch have an impedance product which is substantially constant at all frequencies of interest and each comprises an impedance-transforming attenuator terminated in a fixed impedance. Each attenuator includes means for simultaneously changing both its attenuation and its ratio of impedance transformation. As a special case, the attenuation of the equalizer may be kept substantially constant at an arbitrarily selected frequency, as the equalizer is adjusted to obtain various proportional parts of a desired discrimination characteristic. Each attenuator will, in general, comprise three resistors connected in a T or π formation.

The nature of the invention will be more fully understood from the following detailed description and by reference to the accompanying drawings, of which

Fig. 1 is a schematic circuit of an equalizer in accordance with the present invention in the form of an unbalanced bridged-T structure;

Figs. 2, 3, 4 and 5 show various forms of the bridging branch of the equalizer to which reference is made in explaining the theory of the invention;

Fig. 6 gives typical attenuation-frequency characteristics at three settings of an adjustable equalizer known to the prior art;

Fig. 7 gives the corresponding characteristics of an adjustable equalizer in accordance with the invention, in which the attenuation at the arbitrarily selected frequency f_s remains unchanged at all settings; and

Fig. 8 shows in detail the circuit of an adjustable equalizer in accordance with the invention in the form of a balanced bridged-T structure.

Taking up the figures in more detail, Fig. 1 shows one embodiment of an equalizer in accordance with the invention in the form of an unbalanced bridged-T network having a pair of input terminals **1**, **2**, to which a suitable source of alternating signals may be connected, and a pair of output terminals **3**, **4**, to which a load of suitable impedance may be connected. The network is a constant-resistance structure of the general type disclosed in United States Patent No. 1,606,817, to G. H. Stevenson, issued November 16, 1926, and, as indicated, has at each end a substantially non-reactive image impedance R_0 which is substantially constant with frequency throughout the operating range. It comprises two equal series resistors each of value R_0, a bridging branch **10** of impedance Z_1 connected between the outer terminals **5** and **6** thereof, and a shunt branch **11** of impedance Z_2 connected between the common terminal **7** of the resistors and a point **8** in the path between terminals **2** and **4**. The impedance Z_1 comprises a four-terminal, impedance-transforming attenuator **N1** terminated in a fixed impedance X_A, and the impedance Z_2 comprises another impedance-transforming attenuator **N2** terminated in a second fixed impedance X_B. As indicated by

the arrows connected by the dot-and-dash line **12**, the networks **N1** and **N2** are adjustable and may be under unitary control. The impedances X_A and X_B have approximately the relationship

$$X_A X_B = R_0^2 \tag{1}$$

and the impedances Z_1 and Z_2 have approximately the relationship

$$Z_1 Z_2 = R_0^2 \tag{2}$$

at all settings of the attenuators **N1** and **N2**. The circuit shown in Fig. 1 may, of course, be transformed into a balanced bridged-T structure of the type shown in Fig. 8, if desired.

The theory underlying the invention will now be explained with the aid of Figs. 2, 3, 4 and 5 showing various bridging branches which may be connected between points **5** and **6** of the network of Fig. 1. As shown in Fig. 2, the bridging branch is first designed as the parallel combination of an impedance X and a resistance R which will provide a desired attenuation-frequency characteristic for the equalizer.

Now, a fraction (or multiple), k, of this characteristic can be obtained to a good approximation by substituting for X and R the impedance X′ and the resistance R′, as shown in Fig. 3, provided the following relationships obtain:

$$R' = \left[e^{kA_0} - 1\right] R_0 \tag{3}$$

and

$$X' = \left[\frac{\sinh\left(\frac{kA_0}{2}\right)}{\sinh\left(\frac{A_0}{2}\right)}\right] X \tag{4}$$

where

$$A_0 = \log_e\left(1 + \frac{R}{R_0}\right) \tag{5}$$

and e has its usual significance. If the impedance X is a pure reactance, an equalizer employing the bridging branch shown in Fig. 3 will have exactly k times the attenuation of an equalizer using the branch shown in Fig. 2 at frequencies where the attenuation is zero, maximum, or half the maximum value. At other frequencies in the operating range the proportionality will not be exact, but will be closely approximated.

Proceeding further, the impedance X′ shown in the bridging branch of Fig. 3 may be replaced by an impedance X_1, and the shunt resistance R′ by an L-type attenuator comprising a series resistance R_1 and a shunt resistance R_2, as shown in Fig. 4. An equalizer with a bridging branch as shown in Fig. 4 will have the same attenuation-frequency characteristic, except for an added constant loss of A_1 nepers, as one with the branch shown in Fig. 3 if the following relationships are satisfied:

$$R_1 = \left[\frac{2\sinh\left(\frac{A_1}{2}\right)\sinh\left(\frac{A_1+kA_0}{2}\right)}{\sinh\left(\frac{kA_0}{2}\right)}\right] R_0 \tag{6}$$

$$R_2 = \left[e^{A_1+kA_0} - 1\right] R_0 \tag{7}$$

$$X_1 = \left[\frac{\sinh\left(\frac{A_1+kA_0}{2}\right)}{\sinh\left(\frac{kA_0}{2}\right)}\right]^2 X' \tag{8}$$

In particular, if the magnitude of A_1 is fixed by the relationship

$$\sinh\left(\frac{A_1+kA_0}{2}\right) = \left[\sinh\left(\frac{A_0}{2}\right)\sinh\left(\frac{kA_0}{2}\right)\right]^{1/2} \tag{9}$$

then the impedance X_1 will be equal to X and thus any desired fraction, k, of the original characteristic of the equalizer employing the branch shown in Fig. 2 can be obtained (except for the added constant loss A_1) with the original fixed impedance X. Since any desired proportional part of the original discrimination characteristic can be realized in this manner, it is possible to obtain an adjustable equalizer through an appropriate selection or adjustment of the resistances R_1 and R_2 of Fig. 4, as indicated by the arrows, while having the impedance X_1 fixed. Typical attenuation-frequency characteristics thus obtainable, with values of k equal to unity, 5/6, 1/3 and 1/6, are shown by the curves **13**, **14**, **15** and **16**, respectively, in Fig. 6. In this figure, and also in Fig. 7, a logarithmic frequency scale is used.

In many applications of adjustable equalizers it is desired that the loss of the equalizer at an arbitrarily selected frequency, such as f_S in Fig. 7, remain fixed for all steps in the adjustment, a feature unobtainable with equalizers of the prior art. However, in accordance with the present invention this may be accomplished by an equalizer whose bridging branch **10** has the configuration shown in Fig. 5, comprising a network **N1** terminated in an impedance X_A. The network **N1** is a four-terminal, impedance-transforming attenuator in which both the ratio of impedance transformation and the attenuation may be selected or adjusted to have the required values. At least three impedance branches are required for the network, and these may be arranged in the form of either a **T** or a π structure. As shown, the network **N1** is of the **T**-type, comprising two series resistances R_A and R_C, with a shunt resistance R_B interposed therebetween. In order to facilitate adjustment of the network, each of these resistances may be made adjustable, as indicated by the arrows, and may be placed under unitary control, as indicated by the dot-and-dash line **17**.

Typical attenuation-frequency characteristics thus obtainable are shown in Fig. 7, where the curves **19**, **20**, **21** and **22** correspond, respectively, to a k of unity, 5/6, 1/3, and 1/6 and each has the same attenuation at the arbitrarily chosen frequency f_S of 0.25 megacycle. Since these characteristics are of the type having a maximum loss at a finite frequency, they will also cross at a second common frequency f_X, which is 4 megacycles in this case. To obtain these characteristics, a second loss of A_2 nepers, constant with frequency but dependent on k, is added to each of the characteristics of Fig. 6. The impedances shown in Fig. 5 have the following values in terms of impedances already known:

$$R_A=[e^{A2}]R_1 \qquad (10)$$

$$R_B=[e^{A2}]R_2 \qquad (11)$$

$$R_C=[e^{A2}-1]R_0 \qquad (12)$$

$$X_A=[e^{A2}]X_1 \qquad (13)$$

The value of the impedance X_A as thus determined is not constant, since it depends upon A_2 which, in turn, varies with the value of k. However, it will be noted that, for equal losses A_1 and A_2, the impedance-multiplying factor in Equation 8 is much larger than the corresponding factor in Equation 13. It follows, therefore, that by a readjustment of the relative proportions of A_1 and A_2 the desired result of an invariable impedance X_A with a constant loss at a selected frequency can be obtained.

The formulas giving the required losses A_1 and A_2 are quite involved, so that a method of successive approximations affords the easiest means for solving for their values. The following method is suggested. Let f_S be the frequency at which it is desired to maintain a fixed loss for all values of k, and let A_S be the loss at this frequency when $k=1$. Find (A_1+kA_S) as a function of k, using Equation 9 to determine A_1. The quantity (A_1+kA_S) will have a maximum for some value of k. If the maximum occurs when $k=1$, choose a loss A_2 such that the sum S, given by

$$S=A_1+A_2+kA_S \qquad (14)$$

is equal to this maximum for all values of k. Then, for each k, readjust the values of A_1 and A_2 by successive approximations, keeping their sum a constant such that the overall impedance-multiplying factor is equal to unity, as given by the equation

$$\left[\frac{\sinh^2\left(\frac{A_1+kA_0}{2}\right)}{\sinh\left(\frac{A_0}{2}\right)\sinh\left(\frac{kA_0}{2}\right)}\right]e^{A_2}=1 \qquad (15)$$

If, on the other hand, the maximum value of (A_1+kA_S) should occur when $k<1$, this procedure would require a negative value of A_1, to satisfy Equation 15 when $k=1$, and an alternative procedure must be followed. Choose a trial sum S slightly higher than the maximum value of (A_1+kA_S). Find A_2 for $k=1$, and compute e^{A_2} for this case. The object is to find values of A_1 and A_2 such that the overall impedance-multiplying factor will satisfy the equation

$$\left[\frac{\sinh^2\left(\frac{A_1+kA_0}{2}\right)}{\sinh\left(\frac{A_0}{2}\right)\sinh\left(\frac{kA_0}{2}\right)}\right]e^{A_2}=e^{A_{21}} \qquad (16)$$

where A_{21} is the value of A_2 for $k=1$.

Examining first the value of k which gives the maximum (A_1+kA_S), it will be found that too low a choice of S will require a negative value of A_2 to satisfy Equation 16. Too high a choice of S will result in more added loss in the equalizer than necessary. The optimum choice is that which makes $A_2=0$ for the value of k corresponding to maximum (A_1+kA_S). After the appropriate value of S has been determined, Equation 16 can be satisfied for each value of k by readjusting the values of A_1 and A_2 by successive approximations, keeping S fixed.

Finally, the element values may be determined using Equations 10 to 13 inclusive. In this manner the resistance values are obtained at discrete steps, k, in the adjustment. If the adjustment is to be continuous, intermediate values can be obtained by plotting and interpolation.

In the theory outlined, it is assumed that the fixed impedance branches comprise pure reactance networks. Although this represents the most important case in practical applications, the fixed impedance branches may comprise generalized impedances provided any equivalent parallel resistance in the branch is associated with network **N1**.

The values of all the elements of the bridging branch shown in Fig. 5 have now been determined. This branch may be used for the corresponding one shown in Fig. 1. The impedance of the branch X_B is found from Equation 1. The network N2 is determined by the relationship given in Equation 2. The network N1 may, if desired, be transformed into an equivalent π network. Likewise, the network N2 may be either of the **T** type or the π type.

Fig. 8 is a schematic circuit of an equalizer in accordance with the invention in the form of a balanced bridged-**T** structure which will provide the characteristics shown in Fig. 7. Each of the networks **N11** in the bridging branches is the same as the network N1 of Fig. 5, except that each of the resistances in **N11** has only half the value of the corresponding one in N1. Each of the series resistances has a value of $R_0/2$. Each of the networks **N11** is terminated in an impedance $X_A/2$ comprising three parallel arms. One of these arms is an inductance L_1, another is a capacitance C_1, and the third is made up of inductance L_2 and a capacitance C_2 in series.

The shunt impedance branch Z_2 comprises a network **N2** terminated in an impedance X_B. The network **N2** is a **T**-type structure comprising two series resistances R_X and R_Z and an interposed shunt resistance R_Y. The impedance X_B comprises the parallel combination of an inductance L_4 and a capacitance C_4, in series with an inductance L_3 and a capacitance C_3.

All of the elements in the branches $X_A/2$ and X_B may be fixed in value. However, provision is made for changing both the ratio of impedance transformation and the attenuation of the networks **N11** and **N2**. This may be done by substituting resistances of the required value or, as indicated by the arrows and the connecting dot-and-dash lines, the component resistances may be made adjustable under unitary control.

To provide the characteristics shown in Fig. 7, the reactive elements of Fig. 8 will have approximately the following values when the image impedance R_0 is 110 ohms, the frequency f_S of invariable loss is 0.25 megacycle, and A_0 is 0.4385 neper:

C_1=577 micro-microfarads
C_2=675 micro-microfarads
C_3=1338 micro-microfarads
C_4=293 micro-microfarads
L_1=8.10 microhenries
L_2=1.773 microhenries
L_3=3.492 microhenries
L_4=4.09 microhenries

Each of the resistances $R_0/2$ has a value approximately equal to 55 ohms.

For the curve **20** of Fig. 7, corresponding to $k=5/6$, A_1 may be taken as 0.0395 neper and A_2 as 0.0213 neper. The component resistances in the networks **N11** will then have approximately the following values:

$$R_A/2=1.18 \text{ ohms}$$
$$R_B/2=28.0 \text{ ohms}$$
$$R_C/2=2.46 \text{ ohms}$$

For the curves corresponding to other values of k, these resistances will have other values, determined as explained above, such that the loss of the equalizer at the frequencies f_S and f_X always remains the same.

What is claimed is:

1. An equalizer of the bridged-T type comprising two series resistors, an interposed shunt branch, and a bridging branch, said branches having an impedance product which is substantially constant at all frequencies and each comprising a four-terminal, impedance-transforming attenuator and a fixed reactive impedance connected to the output terminals of said attenuator, the input terminals of one of said attenuators being connected to the outer terminals of said resistors, an input terminal of the other of said attenuators being connected to the common terminal of said resistors, and each of said attenuators comprising three unequal resistances connected to form a ladder-type network and including means for changing the value of each of said three resistances, whereby the attenuation of the equalizer may be kept substantially constant, at an arbitrarily selected frequency, when said resistances in said attenuators are changed to obtain different proportional parts of the discrimination characteristic of the equalizer.

2. An equalizer in accordance with claim 1 in which said two series resistors are approximately equal in value.

3. An equalizer in accordance with claim 1 in which said three resistances in each of said attenuators are connected to form a T network.

4. An equalizer of the bridged-T type comprising two approximately equal resistances connected in series, a shunt branch interposed between said resistances, and a bridging branch connected between the outer terminals of said resistances, the product of the impedances of said branches being substantially constant throughout the frequency range of interest, each of said branches comprising a four-terminal, impedance-transforming attenuator and a fixed reactive impedance connected to the output terminals of said attenuator, the input terminals of one of said attenuators being connected to said outer terminals of said resistances, an input terminal of the other of said attenuators being connected to the common terminal of said resistances, and each of said attenuators comprising three unequal resistances connected to form a ladder-type network and including means for changing the values of said three resistances to other values so chosen as to provide a proportional part of the original discrimination characteristic of the equalizer throughout said range without changing the attenuation at an arbitrarily selected frequency.

5. An equalizer in accordance with claim 4 in which said three resistances in each of said attenuators are connected to form a T network.

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