Jan. 24, 1961 J. T. BANGERT 2,969,509
MINIMUM-PHASE WAVE TRANSMISSION NETWORK
WITH MAXIMALLY FLAT DELAY
Filed Nov. 19, 1958

FIG. 1

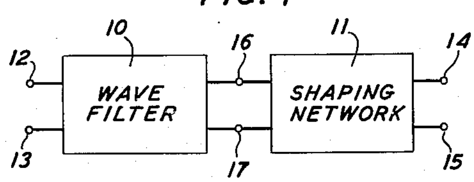


FIG. 5

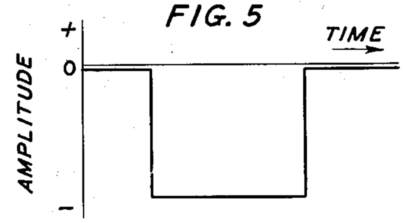


FIG. 2

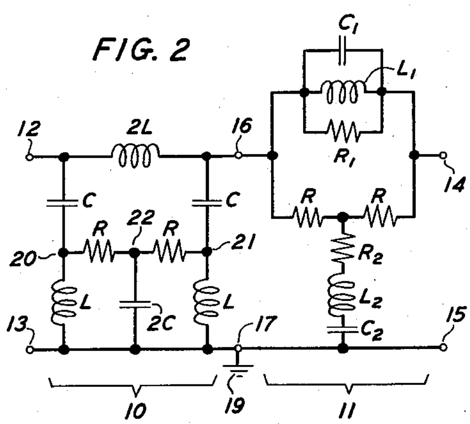


FIG. 6

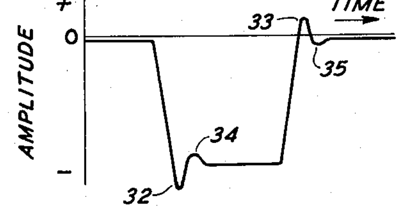


FIG. 7

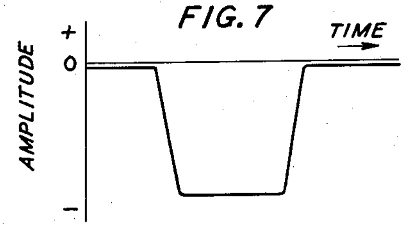


FIG. 4

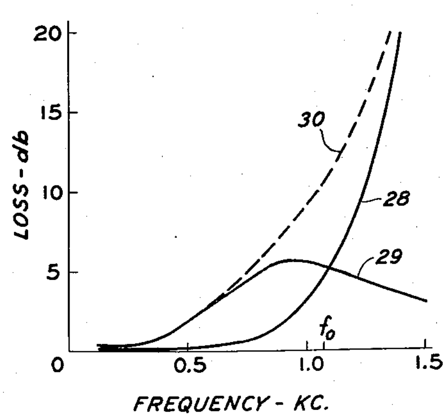
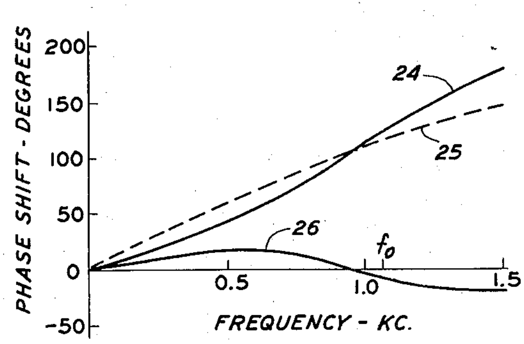


FIG. 3



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2,969,509

MINIMUM-PHASE WAVE TRANSMISSION NETWORK WITH MAXIMALLY FLAT DELAY

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1 Claim. (Cl. 333—28)

This invention relates to wave transmission networks and more particularly to frequency-discriminatory networks of the constant-resistance, minimum-phase type with maximally-flat delay.

The object of the invention is to improve the unit-step response of a two-port, frequency-discriminatory network having a constant-resistance image impedance at each port. More specifically, the object is to eliminate overshoot and ripple in the unit-step response of such a network.

Special requirements apply to two-port, wave transmission networks intended for use in systems which must faithfully transmit rectangular or steep-fronted pulses. One usual requirement is that the image impedance at each port must be substantially a constant, pure resistance at all frequencies of interest, both within and without the transmission band. Another important requirement is that the amplitude response to a rectangular pulse, on a time basis, should be free from objectionable overshoot or ripples. It is known that a minimum-phase network having a maximally-flat delay characteristic will have a satisfactory unit-step response. Some constant-resistance networks of this type heretofore known have minimum phase, but none have maximally-flat delay.

The present invention overcomes this difficulty in a composite, frequency-discriminatory network which includes a wave filter and a shaping network, each of the constant-resistance, minimum-phase type. The shaping network has a delay characteristic which substantially compensates for the departure of the filter from the maximally-flat type throughout the transmission band of the filter. Thus, the composite structure is constant-resistance at each port and has an excellent step-response characteristic.

The filter, which largely determines the insertion loss-frequency characteristic of the composite network, may be of the low-pass, high-pass, band-pass, or band-elimination type. The bridge-type, constant-resistance, minimum-phase filters disclosed in Patent 2,043,345, to S. Bobis, issued June 9, 1936, are preferred because they are minimum phase and may be built in the unbalanced form with a minimum number of elements. The shaping network is preferably a constant-resistance, bridged-T structure of the type disclosed in Patent 1,606,817, to G. H. Stevenson, issued November 16, 1926, which is also minimum phase and may be constructed in the unbalanced form.

The nature of the invention and its various objects, features, and advantages will appear more fully in the following detailed description of a typical embodiment illustrated in the accompanying drawing, of which

Fig. 1 is a block diagram of a composite, frequency-discriminatory, wave transmission network in accordance with the invention;

Fig. 2 is a schematic circuit of an embodiment of the network of Fig. 1 in a low-pass filter;

Fig. 3 shows typical phase shift-frequency characteristics for the filter, the shaping network, and the composite structure of Fig. 2;

Fig. 4 shows the corresponding insertion loss-frequency characteristics for the filter, the shaping network, and the over-all network;

Fig. 5 represents a rectangular voltage pulse used in testing the network; and

Figs. 6 and 7 show the amplitude response-time characteristics obtained at the output end of the filter alone and of the composite network, respectively, when the pulse of Fig. 5 is applied to the input terminals.

As shown in Fig. 1, the composite network comprises a wave filter **10** and a shaping network **11** connected in tandem between a pair of input terminals **12**, **13** and a pair of output terminals **14**, **15**, with intermediate, common terminals **16**, **17**. The filter **10** and the network **11** are each of the constant-resistance, minimum-phase type.

In the embodiment shown in Fig. 2, the filter **10** is an unbalanced, low-pass structure of the type disclosed in Fig. 4 of the above-mentioned Bobis patent. The terminals **13**, **15**, and **17** may be grounded, as indicated at **19**. The circuit comprises two resistors, each having a value R equal to the image impedance at each end, three inductors, and three capacitors. Two of the inductors each have a value L, and the third a value of 2L, where

$$L=R/\sqrt{2}\omega_0 \tag{1}$$

$$\omega_0=2\pi f_0 \tag{2}$$

and f_0 is the nominal cut-off frequency of the filter **10**. Two of the capacitors each have a value C given by

$$C=L/R^2=1/\sqrt{2}R\omega_0 \tag{3}$$

and the third has a value of 2C.

The inductor **2L** is in a bridging branch connected between the high-side input terminal **12** and the corresponding intermediate terminal **16**. A shunt impedance branch comprising C and L in series, with L grounded, is connected between the input terminals **12** and **13**. A similar shunt branch is connected between the intermediate terminals **16** and **17**. The resistors are connected in series between the midpoints **20** and **21** of the two shunt branches. The capacitor 2C is connected between the common terminal **22** of the resistors and ground.

The shaping network **11** in this embodiment is an unbalanced, bridged T structure of the type disclosed in the Stevenson patent mentioned above. The circuit comprises two series resistors each of value R, and interposed shunt branch, and a bridging branch. The bridging branch includes a capacitor of value C_1, an inductor of value L_1, and a resistor of value R_1 connected in parallel between an intermediate terminal **16** and an output terminal **14**. The shunt branch is made up of the series combination of a resistor R_2, and inductor L_2, and a capacitor C_2.

It is recognized that a minimum-phase network with maximally-flat delay will have a unit-step response substantially without overshoot or ripple. The curve **24** of Fig. 3 shows the phase shift-frequency characteristic of the filter **10** when f_0 is 1.06 kilocycles. The broken-line curve **25** shows the phase characteristic required for a maximally-flat delay from zero frequency to f_0. It will be seen that the curve is substantially linear throughout most of the transmission band, but departs more and more from linearity in the neighborhood of f_0 and above. The corresponding delay characteristic will be substantially flat and without ripples over a large part of the pass band but will round off smoothly and monotonically as the cut-off is approached. The flat portion may be extended by increasing the number or complexity of the sections in the composite network. The curve **26** shows the difference between the curves **24** and **25**, and therefore the required phase shift for the shaping network **11**. The curve **26** will be closely matched if the component elements have the following values:

$$C_1=1/ab\omega_0 A \quad (4)$$
$$C_2=a/b\omega_0 R \quad (5)$$
$$L_1=aR/b\omega_0 \quad (6)$$
$$L_2=R/ab\omega_0 \quad (7)$$
$$R_1=R/g \quad (8)$$
$$R_2=gR \quad (9)$$

where a, b, and g are equal, respectively, to 0.655, 0.908, and 1.05.

In Fig. 4, the curves **28**, **29**, and **30** show the insertion loss-frequency characteristics, respectively, for the filter **10** alone, the shaping network **11** alone, and the composite structure. In a minimum-phase structure, the loss is uniquely related to the phase shift. Therefore, if desired, the shaping network **11** may be designed to have the loss shown by the curve **29**. Then, the phase shift will be as shown by the curve **26** of Fig. 3, and the delay will be maximally flat, as desired.

The improvement obtained by adding the shaping network **11** is apparent from a comparison of the amplitude response-time characteristics shown in Figs. 6 and 7. In each case, a negative voltage pulse, of the type shown in Fig. 5, was applied for approximately 0.004 second to the input terminals **12** and **13**. Fig. 6 shows the response at the intermediate terminals **16** and **17**, with the shaping network **11** removed. The overshoot at the points **32** and **33** is about 14 percent, and disturbing ripples appear at the points **34** and **35**. Fig. 7 shows the response at the output terminals **14** and **15**, with the network **11** added. It is seen that the overshoot and the ripples have been reduced to a negligible value.

It is to be understood that the above-described arrangement is only illustrative of the application of the principles of the invention. Numerous other arrangements may be devised by those skilled in the art without departing from the spirit and scope of the invention.

What is claimed is:

A frequency-discriminatory wave transmission network of the minimum-phase type with a constant-resistance image impedance at each end and a maximally-flat delay comprising the tandem-connected combination of a wave filter and a shaping network each of the minimum-phase type and each having at each end an image impedance which is a substantially constant resistance at all frequencies, the filter having a delay characteristic which departs from maximum flatness and the shaping network having a delay characteristic which subtantially compensates for this departure throughout the transmission band of the filter, whereby the composite Network has both the proper insertion loss and the proper phase shift to eliminate substantially all overshoot and ripple in its unit-step response.

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