

May 3, 1938.

E. LAKATOS

2,115,818

WAVE TRANSMISSION NETWORK

Filed Dec. 18, 1935

3 Sheets-Sheet 1

FIG. 1

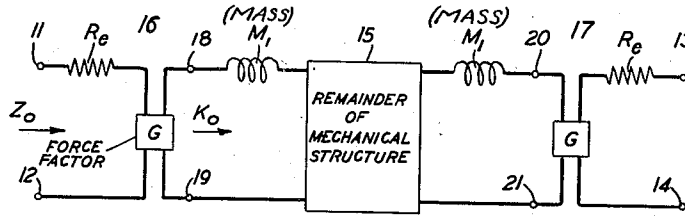


FIG. 2

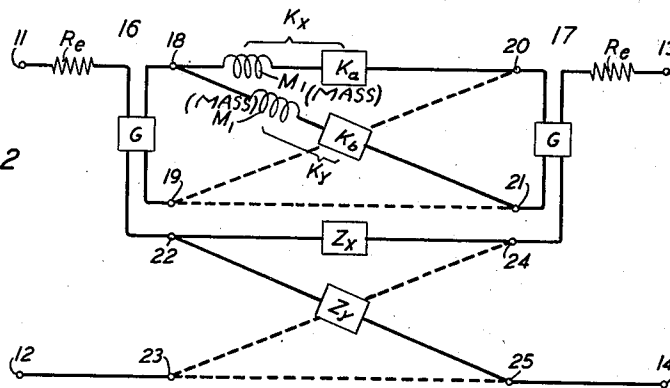


FIG. 3

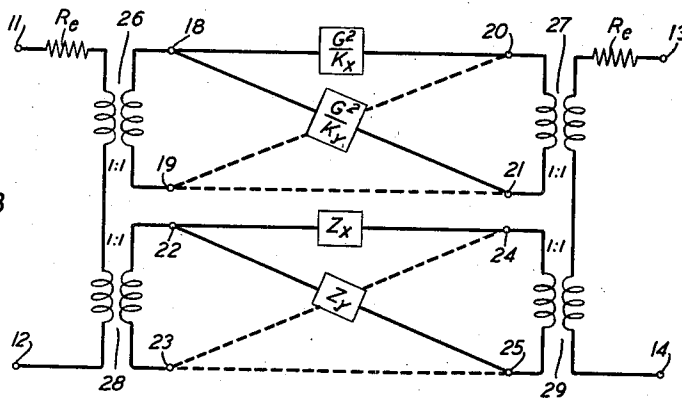
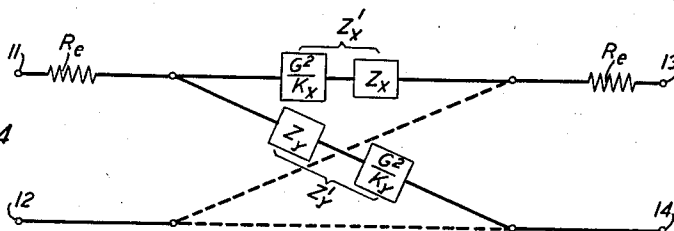


FIG. 4



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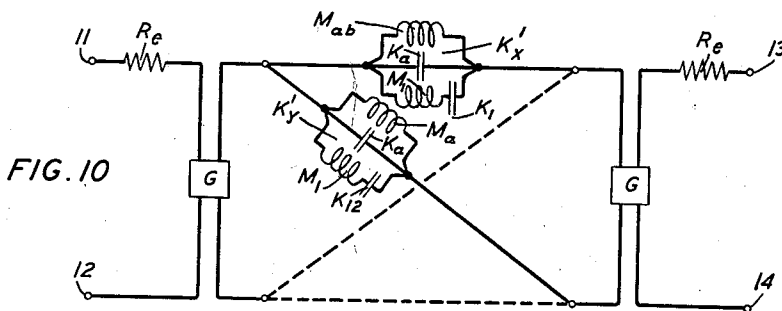
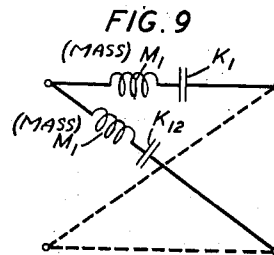
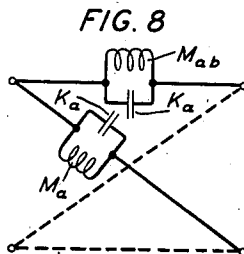
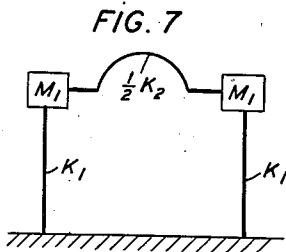
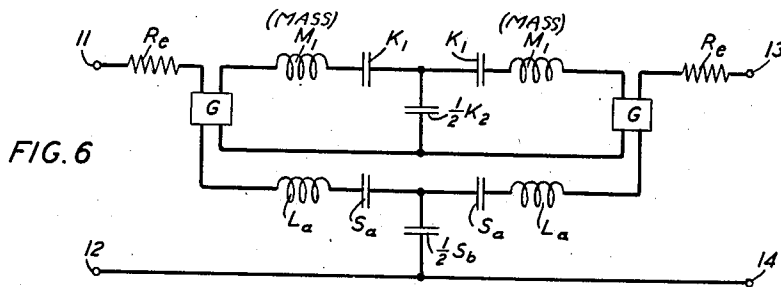
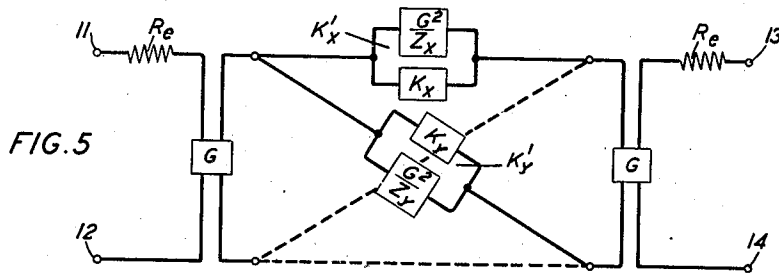
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3 Sheets-Sheet 2



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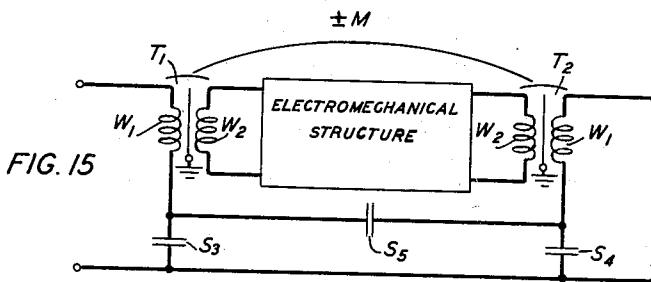
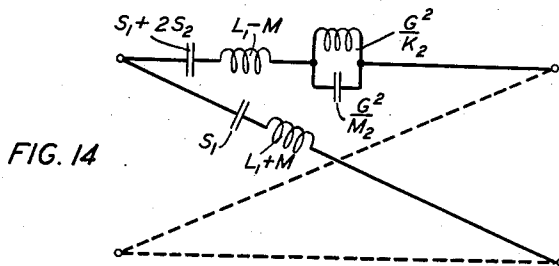
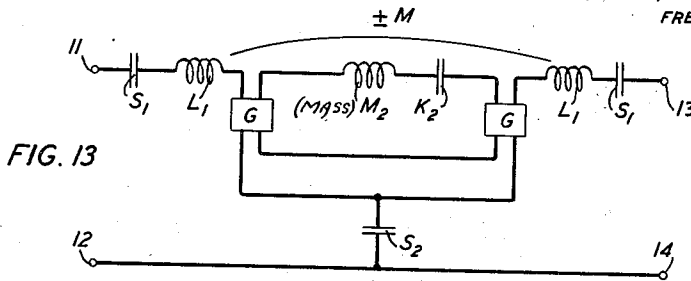
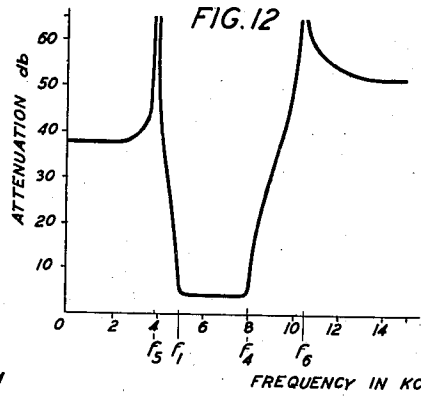
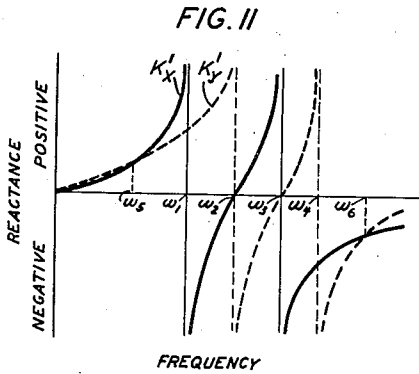
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WAVE TRANSMISSION NETWORK

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3 Sheets-Sheet 3



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2,115,818

WAVE TRANSMISSION NETWORK

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Application December 18, 1935, Serial No. 55,048

12 Claims. (Cl. 178—44)

This invention relates to transmission networks and more particularly to electromechanical wave filters of the composite type in which one or more auxiliary electrical paths are provided either in series or in parallel with the normal path through the mechanical structure.

An object of the invention is to reduce the fixed loss within the transmission band of electromechanical wave filters.

Another object is to increase the width of the transmission bands obtainable, including the provision of low-pass and high-pass filters.

A further object is to lower the mechanical image impedance level obtainable in filters of this type.

Electromechanical wave filters offer a number of important advantages over purely electrical filters, especially in the matter of size, cost and low internal dissipation. Heretofore, however, such filters have been somewhat handicapped by limitations on the maximum band width obtainable, the rapid increase in the fixed losses with increasing band width and the inflexibility in the types of attenuation characteristics they offer.

In accordance with the present invention these limitations are largely overcome by associating with the electromechanical filter an auxiliary electrical network connected effectively either in series or in parallel with the mechanical structure. This electrical network may be a four-terminal structure of any desired degree of complexity, but in the preferred embodiments the energy dissipation therein is confined to end series or shunt elements in order to minimize the fixed loss and attenuation distortion in the transmission band. The electromechanical structures to which the invention is applicable may employ coupling transducers of either the electrostatic or the electromagnetic type, and in the latter case may comprise either moving conductors or moving armatures. Wave filters having low-pass, high-pass, band-pass or multi-band attenuation characteristics may be provided.

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 representation of a mechanical wave transmission network with its associated coupling transducers;

Fig. 2 shows diagrammatically an embodiment of the invention in which a mechanical transmission path and an auxiliary electrical transmission path are provided between a pair of input terminals and a pair of output terminals;

Fig. 3 is an equivalent electrical circuit for the structure of Fig. 2 in which the mechanical network and the electrical network are represented by their equivalent lattices;

Fig. 4 represents schematically a single lattice network which is the electrical equivalent of the composite structure of Fig. 2;

Fig. 5 is a diagrammatic representation of a single lattice network which is the equivalent of the composite structure of Fig. 2 referred to the mechanical side;

Fig. 6 represents diagrammatically an embodiment of the invention in which both the mechanical structure and the electrical structure are ladder-type networks;

Fig. 7 shows diagrammatically a mechanical structure which may be used to provide the mechanical portion of the network of Fig. 6;

Fig. 8 gives the equivalent lattice of the electrical network of Fig. 6, referred to the mechanical side;

Fig. 9 shows the lattice equivalent of the mechanical structure of Fig. 6;

Fig. 10 shows one possible single lattice equivalent for the composite structure of Fig. 6 following the configuration of Fig. 5;

Fig. 11 shows typical reactance characteristics for the impedance branches of Fig. 10;

Fig. 12 shows a typical attenuation characteristic obtainable with the composite network of Fig. 6;

Fig. 13 shows another embodiment of the invention in which electrical impedances are connected in series with the mechanical structure and an auxiliary electrical path is provided between the input terminals and the output terminals;

Fig. 14 shows one possible lattice equivalent for the composite network of Fig. 13, referred to the electrical side; and

Fig. 15 shows another embodiment of the invention in which the electrical network is coupled to the electromechanical structure by transformers.

Fig. 1 represents diagrammatically an electromechanical wave transmission network having a pair of input terminals 11, 12 and a pair of output terminals 13, 14 by means of which the network may be connected between two sections of an electrical transmission line or to other terminal loads of suitable impedance. The network comprises a mechanical structure 15 and the two coupling transducers 16 and 17 on respective sides thereof. Each transducer is represented as comprising an electrical resistance R_e and a mass M_1 coupled by the force factor G . The image impedance on the mechanical side, seen at terminals 18 and 19, is K_o . The image impedance Z_o on the electrical side, seen at terminals 11 and 12, is

$$\frac{G^2}{K_o}$$

In order to minimize reflection effects it is desirable to terminate the network at each end in

a load impedance Z_L which is equal to Z_0 reduced by the value of the resistance R_e connected effectively in series therewith. In equation form

$$Z_L = \frac{G^2}{K_0} - R_e \quad (1)$$

In magnetic transducers of the moving conductor type, shown by way of example in Fig. 1, the relations between the minimum mass of the moving system, the electrical resistance and self-inductance of the transducer, and the density of the biasing flux are such that the maximum absolute band width in a band-pass structure has a definite limit. Also with such structures it is very difficult to provide high-pass or low-pass filters, and the possible attenuation characteristics are decidedly limited. The limitation on band width is due to the fact that it is necessary to utilize the mass M_1 as a component element of the mechanical structure. The magnitude of this mass and the width of the transmission band determine the image impedance level K_0 on the mechanical side. For a given mass, the greater the band width, the greater is the value of K_0 . From Equation (1) it is seen, however, that for proper termination of the filter on the electrical side it is necessary that

$$\frac{G^2}{K_x}$$

shall always be greater than R_e . Since G , M_1 and R_e are not independent of one another it follows that the width of band procurable is therefore limited. In the network shown in Fig. 1 the widest bands may be obtained when the moving conductor is made of material whose density times its resistivity is a minimum, and the biasing flux density is as great as can be procured. However, even with the most efficiently designed electromechanical structures of the type described above, it is found that filters having band widths of 500, 1000, 2000, 3000 and 4200 cycles per second will have fixed losses in the band, due to the effect of the electrical resistance R_e , approximately equal, respectively to 1.1, 2.4, 5.6, 10.9 and ∞ decibels.

In accordance with the present invention the limitations mentioned above are overcome to a large extent by the addition of a suitable auxiliary electrical network. As shown in Fig. 2 this auxiliary network may be a four-terminal structure with its input terminals 22, 23 connected in series with the input terminals 11, 12 of the electromechanical network, and with its output terminals 24, 25 connected in series with the terminals 13, 14. The terminals of the two networks may, of course, be connected together in other ways. For example, the networks may be connected in parallel at both the input and the output ends, or they may be connected in parallel at one end and in series at the other end. However, the series connection at both ends, as shown in Fig. 2, has the advantage that the electrical resistance R_e of the coupling transducers is effectively in series with the load impedances and may readily be taken into account.

For convenience in demonstration both networks are assumed to be symmetrical, and in Fig. 2 are represented by their lattice equivalents. As shown, the mechanical network comprises a pair of series impedance branches K_x each made up of a mass M_1 and an impedance K_a in series, and a pair of diagonal impedance branches K_y consisting of M_1 in series with an impedance K_b . The electrical network comprises series impedance branches Z_x and diagonal branches Z_y . Only

one series branch and one diagonal branch are shown in detail in each network, the other branch constituting the pair being indicated by a dotted line connecting the appropriate terminals. In physical structure either of the networks may be of the lattice, ladder, bridged-T or any other suitable type, it being understood that the circuit shown represents the lattice equivalent in any case, as stated above.

In order to analyze the possible transmission characteristics obtainable with the system of Fig. 2, it is convenient to consider the all-electrical equivalent circuit shown in Fig. 3. The mechanical network may be represented as isolated from the system by the two ideal transformers 26 and 27 of 1:1 ratio which are in effect supplied by the coupling transducers 16 and 17. The relative poling of these transformers can be changed as desired by reversing one pair of leads or by reversing the direction of the biasing flux in one of the transducers. As will be more fully explained hereinafter, different attenuation characteristics may be obtained depending upon the poling of these transformers. Fig. 3 shows the equivalent lattice obtainable with one poling. If the poling of one transformer is reversed the series and diagonal branches of the network are interchanged. The electrical network also may be represented as connected to the system through the two ideal transformers 28 and 29 of 1:1 ratio, as indicated in the figure.

As is well known, the two lattice networks of Fig. 3 are equivalent to a single lattice having series impedance branches Z_x' each comprising the impedances Z_x and

$$\frac{G^2}{K_x}$$

in series, and diagonal branches Z_y' consisting of the impedances Z_y and

$$\frac{G^2}{K_y}$$

in series, as shown schematically in Fig. 4. The all-mechanical equivalent lattice for the system of Fig. 4 is shown in Fig. 5, in which each series impedance branch K_x' consists of the impedances K_x and

$$\frac{G^2}{Z_x}$$

in parallel, and each diagonal branch K_y' comprises the impedances K_y and

$$\frac{G^2}{Z_y}$$

in parallel.

A suggested procedure to be followed in designing a wave transmission network in accordance with the invention is first to determine the impedances of the Z_x' and Z_y' branches of the equivalent lattice of Fig. 4. Expressions for these impedances may be derived as soon as the image impedance Z_0 and the desired transfer constant have been selected. These two expressions are then split into arbitrary components such that

$$Z_x' = Z_x + \frac{G^2}{K_x} \quad (2)$$

and

$$Z_y' = Z_y + \frac{G^2}{K_y} \quad (3)$$

the only restriction being that each component shall be realizable by a physical two-terminal network. The required auxiliary electrical network will then be a structure whose equivalent

lattice has the impedance branches Z_x and Z_y , and the mechanical network will be one for which the equivalent lattice has the impedance branches K_x and K_y , the associated coupling transducers having force factors equal to G , as shown schematically in Fig. 2.

It may sometimes be found more convenient in the design procedure first to determine the branches of the all-mechanical equivalent lattice as shown in Fig. 5 and then break down each branch into the required electrical and mechanical components. This method will, of course, result in the same physical structure as was obtained by following the method outlined above.

A great variety of transmission characteristics are obtainable with the composite electrical and mechanical structure of Fig. 2. For example, the network may be designed to provide a low-pass, band-pass, high-pass or multi-band filter. However, when low-pass or high-pass networks are to be built it is desirable, in splitting up the impedances Z_x' and Z_y' , to choose the Z_x and Z_y components of such form that they yield electrical networks which are potentially low-pass or high-pass filters, so that the mechanical structure and its associated transducers will not be called upon to perform functions which are unnatural to them.

An example of a composite electromechanical band-pass filter constructed in accordance with the invention is shown schematically in Fig. 6. The mechanical structure consists of a single ladder-type section mid-series terminated at each end in which each series impedance branch comprises a mass M_1 and a stiffness K_1 in series, and the interposed shunt branch is constituted by a stiffness of value $\frac{1}{2}K_2$. Such a structure may be provided physically, for example, by two masses M_1 , M_1 connected by a spring having a stiffness equal to $\frac{1}{2}K_2$ and each supported from a fixed base by a spring having a stiffness K_1 , as shown diagrammatically in Fig. 7. The two associated coupling transducers, each of which has an electrical resistance R_e and a force factor G , are not shown in Fig. 7, but the construction of such transducers is well known.

The auxiliary electrical network as shown in Fig. 6 is also a single section of the ladder type terminated mid-series at each end. Each series impedance branch comprises an inductance L_a in series with a capacitance of stiffness S_a , and the intervening shunt branch consists of a capacitance having a stiffness equal to $\frac{1}{2}S_b$. The lattice equivalent of the electrical network, referred to the mechanical side, is shown in Fig. 8, in which the impedances K_a , M_a , M_b and M_{ab} are found from the following expressions:

$$K_a = \frac{G^2}{L_a} \quad (4)$$

$$M_a = \frac{G^2}{S_a} \quad (5)$$

$$M_b = \frac{G^2}{S_b} \quad (6)$$

$$M_{ab} = \frac{M_a M_b}{M_a + M_b} \quad (7)$$

The lattice equivalent of the mechanical structure is shown in Fig. 9, where

$$K_{12} = K_1 + K_2 \quad (8)$$

For a certain poling of the electrical connections and a given direction of the steady fluxes in the coupling transducers the equivalent lattice for

the combined network will be as shown in Fig. 10, following the circuit of Fig. 5. In Fig. 10 the series impedance branch of Fig. 8 and the series branch of Fig. 9 have been combined in parallel to form the new series branch K_x' , and likewise the two diagonal branches in parallel form the new diagonal branch K_y' . If the poling is reversed or if the direction of biasing flux is changed in one of the transducers the impedances M_a and M_{ab} of Fig. 10 will be effectively interchanged. The reactance of the series impedance branch K_x' of Fig. 10 is of the form shown by the solid line curve of Fig. 11 and is given by the expression

$$K_x' = \frac{\omega K_a (\omega^2 - \omega_3^2)}{j(\omega^2 - \omega_1^2)(\omega^2 - \omega_3^2)} \quad (9)$$

where ω is equal to 2π times the frequency in cycles per second. The reactance of the diagonal branch is shown by the dotted line curve and is given by

$$K_y' = \frac{\omega K_a (\omega^2 - \omega_3^2)}{j(\omega^2 - \omega_2^2)(\omega^2 - \omega_4^2)} \quad (10)$$

The image impedance K_I on the mechanical side is given by

$$K_I = \frac{\omega K_a}{j\sqrt{(\omega^2 - \omega_1^2)(\omega^2 - \omega_4^2)}} \quad (11)$$

and the image impedance level at mid-band is

$$K_o = \frac{K_a}{\omega_4 - \omega_1} \quad (12)$$

When the impedance K_o has been selected the value of K_a may be found from Equation (12). The values of the remaining elements can be found from the following expressions, derived from Equations (9) and (10).

$$M_a = K_a \left[\frac{\omega_3}{\omega_2 \omega_4} \right]^2 \quad (13)$$

$$M_b = \frac{K_a}{\left[\frac{\omega_1 \omega_3}{\omega_2} \right]^2 - \left[\frac{\omega_2 \omega_4}{\omega_3} \right]^2} \quad (14)$$

$$M_1 = \frac{K_a \omega_3^2}{(\omega_3^2 - \omega_2^2)(\omega_1^2 - \omega_3^2)} = \frac{K_a \omega_2^2}{(\omega_2^2 - \omega_1^2)(\omega_3^2 - \omega_2^2)} \quad (15)$$

$$K_1 = M_1 \omega_2^2 \quad (16)$$

$$K_2 = M_1 (\omega_3^2 - \omega_2^2) \quad (17)$$

The conditions that M_b shall be positive and that the two values of M_1 are equal impose the restrictions that

$$\omega_2^2 = \frac{\omega_1^2}{2 - \left(\frac{\omega_4}{\omega_3} \right)^2} \quad (18)$$

and

$$\left[\frac{\omega_3}{\omega_4} \right]^2 \geq \frac{1 + \frac{\omega_1}{\omega_4}}{2} \quad (19)$$

The network of Fig. 10, and therefore the network of Fig. 6, because of the equivalence of the two circuits, will have a transmission band extending between the two frequencies ω_1 and ω_4 , and will have peaks of attenuation located at ω_3 and ω_2 where the reactance of K_x' crosses the reactance of K_y' . If, for example, the critical frequencies, given by

$$f_i = \frac{\omega_i}{2\pi}$$

are chosen as follows:

$$\left. \begin{aligned} f_1^2 &= 25.0 \times 10^6 \\ f_2^2 &= 31.9 \times 10^6 \\ f_3^2 &= 52.5 \times 10^6 \\ f_4^2 &= 64.0 \times 10^6 \end{aligned} \right\} \quad (20)$$

the resultant attenuation characteristic, having a 3,000 cycle band extending from 5 to 8 kilocycles, will be as shown in Fig. 12. The flat loss in the band does not exceed 4 decibels, compared with 10.9 decibels for the most efficiently designed structure heretofore known having the same band width, as given hereinabove. By the introduction of the auxiliary electrical network, this fixed loss has, therefore, been reduced by a factor greater than two. Another way of stating the same result is to say that the impedance level K_0 on the mechanical side has been greatly reduced, since the magnitude of the electrical resistance R_e is directly dependent upon this impedance level, and the flat loss depends upon the value of R_e .

In order to provide a low-pass filter the two capacitances S_a and S_b of Fig. 6 are removed. As in the case of the preceding example there are two possible lattice structures equivalent to the composite structure. If mutual inductance is introduced between the two inductances L_a and L_b there will be four possible equivalences obtainable. Each of these structures will have a low-pass band, and in certain cases there will also be other transmission bands.

Another embodiment of the invention is shown schematically in Fig. 13. A magnetic receiver having two windings and suitably disposed magnetic armature may, for example, be used to provide the two inductances L_1 , L_2 coupled by a mutual inductance $\pm M$, the mass M_2 and the mechanical stiffness K_2 , the coupling factor being represented by G . Alternatively, the two inductances L_1 , L_2 and the associated mutual inductance $\pm M$ may be furnished by two separate external inductors so arranged as to provide the required coupling. The network is completed by the addition externally of the two series electrical capacitances each having a stiffness S_1 , and the shunt capacitance S_2 . The electrical resistance R_e is not indicated in this figure but it may be taken into account in proportioning the load impedances, as explained above.

Depending upon the sign of the mutual inductance and the direction of the biasing flux four distinct lattice networks equivalent to the structure of Fig. 13 may be obtained. One of these equivalences, as viewed from the electrical side, is shown in Fig. 14. Since every element of the equivalent lattice may be controlled independently there is obtainable a transmission characteristic having two peaks of attenuation which may be placed arbitrarily either on the real frequency axis or in the complex frequency plane. By assigning limiting values to any one of the elements S_1 , S_2 or M , or to any combination of them, other types of characteristics are obtainable. For example, by omitting the capacitances S_1 , S_2 the structure may be designed to provide the equivalent of a four-element band-pass filter section, with a single attenuation peak located on either side of the transmission band as desired. Also, by making the self-inductance of L_1 equal to M there may be obtained two structures which are single band, high-pass filters. For this purpose the mutual inductance M may be made equal to L_1 to a high degree of approximation by winding the input and output inductances as a parallel pair. On the other hand, low-pass filters may be obtained by omitting the two capacitances S_1 and S_2 . The use of the auxiliary electrical elements in the composite structure of Fig. 13 also effects a marked reduction in

the fixed loss within the transmission band, as described above in connection with Fig. 6.

Another embodiment of the invention is shown diagrammatically in Fig. 15 in which the auxiliary electrical network is coupled to the electromechanical structure by means of two transformers T_1 and T_2 . Each transformer has a primary winding W_1 which is loosely coupled to the secondary winding W_2 , and both windings of the one transformer are coupled to both windings of the other transformer by a mutual inductance $\pm M$. The electrical network comprises the two shunt capacitances S_3 and S_4 and an interposed series capacitance S_5 . The electromechanical structure, which is connected between the secondaries of the two transformers, may, for example, be of the stretched wire type disclosed in United States Patent 2,056,281 issued October 6, 1936 to applicant's assignee. The composite structure of Fig. 15 has four distinct lattice equivalents, with the corresponding number of types of attenuation characteristics, as described above in connection with Fig. 13. By the addition of the auxiliary electrical network the flat loss within the band of the mechanical filter can be cut approximately in half, and in addition wider band widths and more diversified attenuation characteristics may be obtained. In some cases a distinct improvement in the attenuation characteristic of the mechanical structure may be obtained by making the auxiliary electrical network a simple shunt resistance of value R . The resistance is used to annul the effect of the mutual resistance R_m effective between the input and output terminals, and its value is found from the equation

$$R = h R_m \quad (21)$$

where h represents the impedance step-up ratio of the transformers T_1 and T_2 . By the addition of the resistance R the attenuation of the filter in the suppressed ranges may be increased as much as 10 decibels.

What is claimed is:

1. A wave transmission network comprising a magnetic receiver having two windings and a suitably disposed magnetic armature, two electrical impedances connected respectively in series with said windings, and a four-terminal electrical network having its input terminals connected in series with one of said windings and its output terminals connected in series with the other of said windings, said two electrical impedances, the impedances comprising said electrical network and the impedances comprising said magnetic receiver being so proportioned that said transmission network as a whole will freely transmit a band of frequencies while attenuating other frequencies, whereby the transmission loss within said band is substantially reduced.

2. A wave transmission network comprising an electromechanical structure, a four-terminal electrical network and two transformers, said electrical network being connected at its ends respectively to the primary windings of said transformers, said electromechanical structure being connected between the secondary windings of said transformers, and the component impedances comprising said electrical network being so proportioned with respect to the component impedances comprising said electromechanical structure that said transmission network as a whole will freely transmit a band of frequencies while suppressing other frequencies, whereby the transmission loss within said band is substantially reduced.

3. A composite electromechanical wave filter comprising a mechanical structure, a pair of coupling transducers at the respective ends thereof for connecting said mechanical structure to a pair of input terminals and a pair of output terminals, and an auxiliary four-terminal electrical network having its input and output connected in series, respectively, with said input and output terminals, said electrical network comprising two series impedance branches and an interposed shunt impedance branch so proportioned that said composite filter as a whole has a cut-off frequency on one side of which there is a band of free transmission and on the other side of which there is region of substantial suppression.

4. A composite electromechanical wave filter in accordance with the preceding claim in which said electrical network has a low-pass attenuation characteristic.

5. An electromechanical wave filter comprising a mechanical structure, a pair of coupling transducers for connecting said mechanical structure to a pair of input terminals and a pair of output terminals, and two series inductances so related as to have a mutual inductance effective therebetween, said inductances being associated with the respective ends of said mechanical structure, and said inductances being so proportioned with respect to the component impedances comprising said mechanical structure that said wave filter freely transmits a band of frequencies while attenuating other frequencies.

6. An electromechanical wave filter in accordance with the preceding claim which provides a low-pass attenuation characteristic.

7. An electromechanical wave filter in accordance with the second preceding claim in which said mutual inductance is substantially equal to the self-inductance of each of said series inductances, whereby a high-pass attenuation characteristic is provided.

8. A composite electromechanical wave filter comprising a pair of input terminals, a pair of output terminals, a mechanical vibratory structure, means for connecting said mechanical structure between said input terminals and said output terminals, and an auxiliary four-terminal electrical network of the ladder type connected between said input and said output terminals, said mechanical structure being designed to transmit a certain band of frequencies while substantially attenuating frequencies lying outside said band, and said auxiliary electrical network being designed to transmit freely the same band, whereby the transmission loss within said band is substantially reduced.

9. A composite electromechanical wave filter

comprising a pair of input terminals, a pair of output terminals, a mechanical vibratory structure, means for connecting said mechanical structure between said input terminals and said output terminals, an inductance associated with the input end of said filter, and an inductance associated with the output end of said filter, said two inductances being so related as to have mutual inductance effective therebetween, and said two inductances being so proportioned with respect to the component impedances comprising said mechanical vibratory structure that said composite wave filter freely transmits a band of frequencies while substantially suppressing frequencies falling outside of said band.

10. A composite electromechanical wave filter comprising a pair of input terminals, a pair of output terminals, a mechanical vibratory structure, means for connecting said mechanical structure between said input terminals and said output terminals, an auxiliary electrical network connected between said input terminals and said output terminals, an inductance associated with the input end of said filter, and an inductance associated with the output end of said filter, said two inductances being so related as to have mutual inductance effective therebetween, and said two inductances being so proportioned with respect to the component impedances comprising said mechanical vibratory structure and said auxiliary electrical network that said composite wave filter freely transmits a band of frequencies while attenuating other frequencies.

11. A composite electromechanical wave filter comprising a pair of input terminals, a pair of output terminals, a mechanical vibratory structure, means for connecting said mechanical structure between said input terminals and said output terminals, an electrical impedance associated with the input end of said filter, an electrical impedance associated with the output end of said filter, and an auxiliary electrical network connected between said input terminals and said output terminals, said two electrical impedances being so proportioned with respect to the component impedances comprising said auxiliary electrical network and said mechanical vibratory structure that said composite wave filter freely transmits a band of frequencies while substantially suppressing other frequencies.

12. A wave transmission network in accordance with claim 2 in which said transformers are so related as to have mutual inductance effective between a winding of one of said transformers and a winding of the other of said transformers.

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