March 28, 1944. W. P. MASON 2,345,491

WAVE TRANSMISSION NETWORK

Filed Nov. 25, 1941

FIG. 1

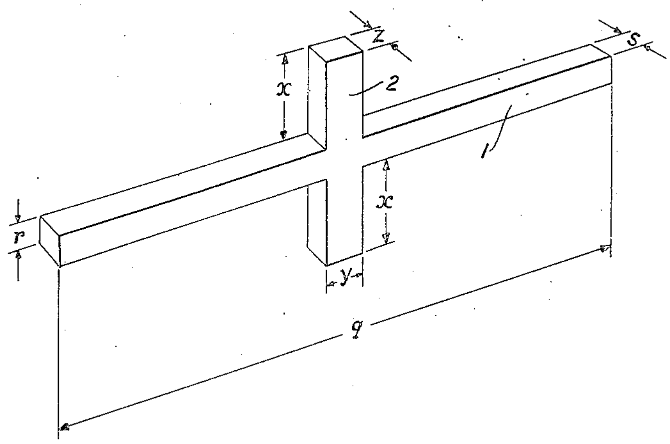
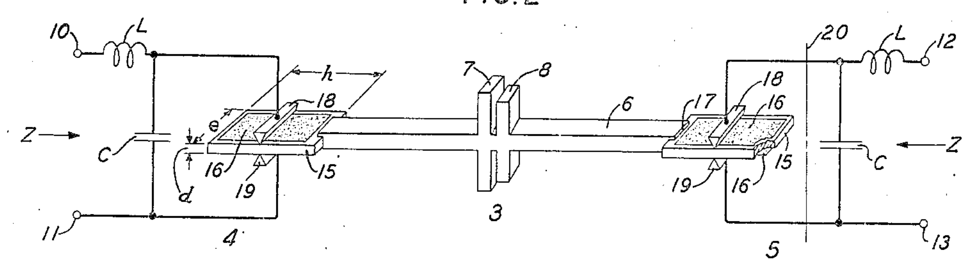


FIG. 2



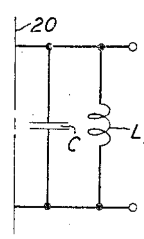


FIG. 3

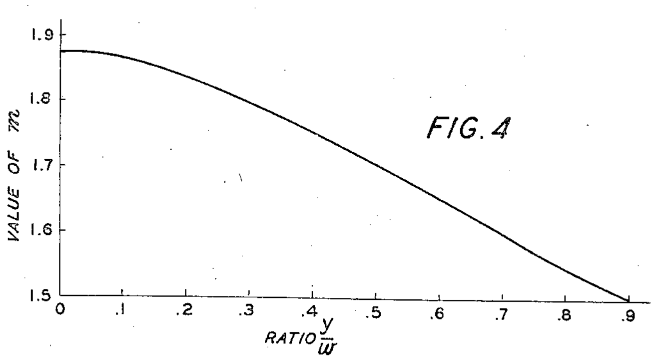


FIG. 4

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WAVE TRANSMISSION NETWORK

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34 Claims. (Cl. 178—44)

This invention relates to wave transmission networks and more particularly to wave filters of the electromechanical type.

Objects of the invention are to improve the attenuation characteristic, increase the width of the band, decrease the size and reduce the cost of electromechanical wave filters.

The wave transmission network in accordance with the invention comprises a mechanical filter and, at each end, an electromechanical converter. The mechanical filter comprises a rod of acoustic material along which the energy is propagated and one or more crossbars of acoustic material, located near the center of the rod, which are set into flexural vibration. Due to the closer mechanical coupling between the rod and crossbar for the flexural mode, as compared with the longitudinal node, a much wider transmission band may be obtained if the crossbar is used in flexure.

The rod has small cross-sectional dimensions compared to its length, which is approximately equal to a half wave-length at the mid-band frequency in the double crossbar filter or at a cut-off frequency in the single crossbar filter. The crossbar extends half on each side of the rod to prevent setting up flexural vibrations along the rod. When a single crossbar is employed it is so proportioned that each half has its first clamped-free antiresonance on either the lower or the upper side of the transmission band to provide a peak of attenuation at that frequency. When two crossbars are used, usually one is made to antiresonate below the band and the other above the band, to provide two attenuation peaks. The two crossbars are located symmetrically about the mid-point of the rod and are placed close together. Such a filter may be designed to have substantially the same attenuation characteristic as two single crossbar filters each requiring a half-wave rod, thus saving one length of rod and reducing the cost.

The electromechanical converter at each end of the mechanical filter comprises a piezoelectric crystal the length of which is approximately equal to a half wave-length at the mid-band frequency. A Rochelle salt crystal, because of its high piezoelectric activity, is well adapted for this use. The end of the crystal is fastened to the end of the rod so that the longitudinal vibrations set up in the crystal are transmitted to the rod. The filter may be supported by clamping each crystal at its mid-point, at which there is a node of motion. The mechanical image impedance of the crystal is of the right type to match the image impedance of the mechanical filter. To improve the electrical impedance of the converter an inductor, connected either in series or in shunt, and in some cases a shunt condenser may be associated with the crystal.

The nature of the invention will be more fully understood from the following detailed description and by reference to the accompanying drawing, in which like reference characters refer to similar parts and in which:

Fig. 1 is a perspective view of a single crossbar mechanical filter in accordance with the invention;

Fig. 2 shows a double crossbar filter with electromechanical converters at its ends;

Fig. 3 shows schematically an alternative connection for the end inductors of Fig. 2; and

Fig. 4 is a curve useful in designing the crossbar.

Taking up the figures in more detail Fig. 1 shows in perspective a mechanical filter in accordance with the invention comprising a single crossbar. The rod 1 is of rectangular cross section having a length q which is long compared to its width r and its thickness s. At the center of the rod 1 is a lateral crossbar 2 which extends perpendicularly for a distance x on each side of the rod 1 and also has a rectangular cross section, of width y and thickness z. The thickness s of the rod 1 and the thickness z of the crossbar 2 may conveniently be made equal. The rod 1 and the crossbar 2 are made of some suitable acoustic material, preferably one having a low temperature-frequency characteristic. Metal, such as aluminum or an alloy, and ceramic material have been found to be satisfactory.

If the filter is to transmit a band extending from the lower cut-off frequency f_1 to the upper cut-off f_2, with a peak of attenuation at a frequency f_A on the lower side of the band, the length of the rod 1 is made equal to a half wave-length at the upper cut-off frequency f_2. That is,

$$q=\frac{v}{2f_2} \qquad (1)$$

where v is the velocity of propagation in the rod 1 and is equal to the square root of the ratio of Young's modulus to the density.

It is to be understood that the rod 1 will have longitudinal vibrations impressed upon one end by means of some driving device. These longitudinal vibrations, acting upon the crossbar 2 at its center, will cause the crossbar to vibrate in the flexural node. The effective length w and the width y of the crossbar are so proportioned that the first clamped-free antiresonance of each half of the crossbar occurs at the frequency f_A. The volume of the crossbar 2 determines the width of the band to be transmitted. In general, a larger volume corresponds to a narrower band. The following two equations must therefore both be satisfied:

$$w^3=\frac{m^2vy}{2\pi f_A\sqrt{12}} \qquad (2)$$

$$\frac{wy}{qr}=\frac{0.66a^2}{1-a^2} \qquad (3)$$

In Equations 2 and 3 m is a factor depending upon the ratio of the width y to the effective length w, the rotary and lateral inertias, the effect of shear and the boundary conditions. A curve of the values of m plotted against the ratio of y to w is given in Fig. 4. A series of measurements on aluminum crossbars has shown that if the width y of the crossbar 2 is approximately equal to the width r of the rod 1 the effective length w used in Equation 2 should be taken as the length x of each crossbar projection plus one-fourth of the width r; that is,

$$w=x+\frac{r}{4} \qquad (4)$$

The factor a is given by

$$a=\sqrt{\frac{1-\left(\frac{f_A}{f_1}\right)^2}{1-\left(\frac{f_A}{f_2}\right)^2}} \qquad (5)$$

The only factor not yet determined in Equations 2 and 3 is the width r of the rod 1. The value of r depends upon the desired image impedance K at the mid-band frequency f_m and is found in terms of the thickness s from the formula

$$K=\frac{\pi\rho rsv(f_2-f_1)}{4f_m}\sqrt{\frac{f_2}{a^2f_1+\left(\frac{\pi}{4}\frac{f_2-f_1}{f_m}\right)^2(f_2+f_1a^2)}} \qquad (6)$$

The mid-band frequency f_m is equal to the square root of the product of f_1 and f_2. The thickness s of the rod 1 may be arbitrarily chosen and, as already pointed out, the thickness z of the bar 2 may conveniently be made equal to s.

To provide a peak of attenuation at a frequency f_B on the upper side of the transmission band the design procedure above outlined is followed except that the length q of the rod 1 is made equal to a half wave-length at the lower cut-off frequency f_1, that is,

$$q=\frac{v}{2f_1} \qquad (7)$$

and the following formulas are used instead of 2, 3 and 6, respectively.

$$w^3=\frac{m^2vy}{2\pi f_B\sqrt{12}} \qquad (8)$$

$$\frac{wy}{qr}=\frac{0.66}{b^2-1} \qquad (9)$$

$$K=\frac{\pi\rho rsv(f_2-f_1)}{4f_m}\sqrt{\frac{f_1b^2}{f_2+\left(\frac{\pi}{4}\frac{f_2-f_1}{f_m}\right)^2(f_2+f_1b^2)}} \qquad (10)$$

The factor b is given by

$$b=\sqrt{\frac{1-\left(\frac{f_B}{f_1}\right)^2}{1-\left(\frac{f_B}{f_2}\right)^2}} \qquad (11)$$

Fig. 2 shows a wave transmission network in accordance with the invention comprising a mechanical filter 3 and, at each end, electromechanical converters 4 and 5 connected in tandem between two pairs of terminals 10, 11 and 12, 13. The network may be designed to transmit a band of frequencies extending from f_1 to f_2, with attenuation peaks at f_A below the band and at f_B above the band. In this case the rod 6, which is similar to the rod 1 of Fig. 1 has a length equal to a half wave-length at the mid-band frequency f_m. The filter has two crossbars, 7 and 8, placed close together and centrally located with respect to the ends of the rod 6. One of the crossbars, for example 7, is proportioned to have its first clamped-free antiresonance at the frequency f_A and the other crossbar has its first clamped-free antiresonance at f_B to provide the two peaks of attenuation.

The width of the transmission band is determined by the ratio of the sum of the masses of the crossbars 7 and 8 to the mass of the rod 6. The position of the band with respect to the peak frequencies f_A and f_B is determined by the ratio of the masses of the two crossbars 7 and 8. If these masses are equal the band is symmetrically located with respect to f_A and f_B. If one of the masses is smaller than the other the band will be displaced toward the peak frequency determined by the crossbar having the smaller mass.

The mechanical filter 3 of Fig. 2, having two crossbars close together, may be designed to have substantially the same attenuation characteristic as two single crossbar filters, of the type shown in Fig. 1, connected in tandem. It is apparent therefore that the two-crossbar filter requires less space, has less weight and costs less to construct.

If the filter shown in Fig. 1 or the filter 3 of Fig. 2 is to be used in an electrical system it is necessary to provide at one end means for converting the electrical vibrations to longitudinal mechanical vibrations and means at the other end for reconverting to electrical vibrations. The electromechanical converters 4 and 5 perform this function. Each converter comprises a piezoelectric crystal 15, a series inductor L and a shunt capacitor C. The crystal 15 is preferably cut from Rochelle salt in the form of a plate the thickness dimension d of which is parallel to the Y axis and the width dimension e and length dimension h of which make angles of approximately 45 degrees with the X and Z axes. Each major face has associated therewith an electrode 16 which may, for example, be tinfoil cemented in place. One end of the crystal 15 is glued or otherwise fastened to the end of the rod 6. To strengthen this joint the rod 6 may be provided at its ends with flanges 17. In practice the thickness of the rod 6 is made equal to about half of the width e of the crystal.

The length h of the crystal 15 is made approximately equal to a half wave-length at the mid-band frequency f_m, that is,

$$h=\frac{v_1}{2f_m} \qquad (12)$$

where v_1 is the velocity of propagation. The crystal will have a node of motion at its center and it may therefore be clamped at this point between a pair of supports 18 and 19 without the introduction of dissipation or undesired nodes of motion. Also, to avoid unwanted nodes, the length h of the crystal should exceed the width e.

Assuming that the width is equal to half of the length

$$e=0.5h \quad (13)$$

The thickness d of the crystal is dependent upon the mechanical image impedance K_1 of the crystal at mid-band and is given by

$$d=\frac{\pi \rho_1 e v_1 (f_2-f_1)}{2 f_m K_1} \quad (14)$$

where ρ_1 is the density of the crystal. The impedance K_1 is usually chosen to match the image impedance K of the mechanical filter 3.

The value of the inductance of the inductor L may be found from the formula

$$L=\frac{Z}{2\pi(f_2-f_1)} \quad (15)$$

where Z is the desired electrical image impedance at the midband frequency f_m.

The value of the capacitance C is given by

$$C=\frac{f_2-f_1}{\pi Z(f_2^2+f_1^2)}-C_1 \quad (16)$$

where C_1 represents the interelectrode capacitance associated with the crystal 15 and may be computed from the area of the electrodes 16, the distance between electrodes and the dielectric constants of the intervening materials. If the transmission band is sufficiently narrow the value of C_1 may equal the value of the fraction in Equation 16, in which case no added capacitor C is required.

The electromechanical converters 4 and 5 of Fig. 2 have an inherently low image impedance Z. If a high image impedance is desired the end inductors may be connected in shunt, as is L_1 in Fig. 3, which shows the portion of the circuit to the right of the line 20 of Fig. 2.

It is to be understood, of course, that the converters 4 and 5, described in connection with Figs. 2 and 3, or equivalent converters, may be used at the ends of the mechanical filter shown in Fig. 1. The attenuation peaks contributed by the cross-bars 2, 7 and 8 are usually placed close to the band limits to provide a sharp cut-off. The converters 4 and 5, however, have attenuation peaks at zero frequency and at infinity and the network as a whole, therefore, has a well-sustained attenuation characteristic outside of the band.

What is claimed is:

1. A wave transmission network for transmitting a band of frequencies comprising a mechanical filter and electro-mechanical means for impressing longitudinal mechanical vibrations upon said filter, said filter including a rod of acoustic material and a crossbar of acoustic material, said crossbar being located near the center of said rod, said rod having a length approximately equal to a half wave-length at a frequency in said band and said crossbar having its dimensions so proportioned that the first clamped-free flexural antiresonance of each half occurs at a frequency close to a limit of said band.

2. A network in accordance with claim 1 in which said electromechanical means include a piezoelectric crystal having a length approximately equal to a half wave-length at the geometric mean of said band of frequencies.

3. A network in accordance with claim 1 in which said electromechanical means include a piezoelectric crystal having a length approximately equal to a half wave-length at a frequency falling within said band, an end of said crystal and an end of said rod being fastened together and said crystal being supported at a node of motion.

4. A network in accordance with claim 1 in which said electromechanical means include a piezoelectric crystal and an associated inductor, said crystal having a length approximately equal to a half wave-length at the geometric mean of said band of frequencies and said inductor having its inductance proportioned with respect to said band of frequencies to provide the desired electrical image impedance for said electromechanical means.

5. A wave transmission network for transmitting a band of frequencies comprising a mechanical filter and electromechanical means for impressing longitudinal mechanical vibrations upon said filter, said filter including a rod of acoustic material and a crossbar of acoustic material, said crossbar being located near the center of said rod, said rod having a length approximately equal to a half wave-length at the upper limiting frequency of said band and said crossbar having its dimensions so proportioned that the first clamped-free flexural antiresonance of each half occurs at a frequency close to the lower limit of said band.

6. A wave transmission network for transmitting a band of frequencies comprising a mechanical filter and electromechanical means for impressing longitudinal mechanical vibrations upon said filter, said filter including a rod of acoustic material and a crossbar of acoustic material, said crossbar being located near the center of said rod, said rod having a length approximately equal to a half wave-length at the lower limiting frequency of said band and said crossbar having its dimensions so proportioned that the first clamped-free flexural antiresonance of each half occurs at a frequency close to the upper limit of said band.

7. A wave transmission network for transmitting a band of frequencies with a certain mid-band frequency comprising a mechanical filter and electromechanical means for impressing longitudinal mechanical vibrations upon said filter, said filter including a rod of acoustic material and two crossbars of acoustic material, said crossbars being located close together near the center of said rod, said rod having a length approximately equal to a half wave-length at said mid-band frequency, one of said crossbars having its dimensions so proportioned that the first clamped-free flexural antiresonance of each half occurs at a frequency close to one limit of said band and the other of said crossbars having its dimensions so proportioned that the first clamped-free flexural antiresonance of each half occurs at a frequency close to the other limit of said band.

8. A network in accordance with claim 7 in which said electromechanical means include a piezoelectric crystal having a length approximately equal to a half wave-length at said mid-band frequency.

9. A network in accordance with claim 7 in which said electromechanical means include a piezoelectric crystal and an associated inductor, said crystal having a length approximately equal to a half wave-length at said mid-band frequency and said inductor having its inductance proportioned with respect to said band of frequencies to provide the desired electrical image impedance for said electromechanical means.

10. A wave transmission network for transmitting a band of frequencies with a certain mid-

band frequency while substantially attenuating frequencies falling outside of said band comprising a mechanical filter and an electromechanical converter, said mechanical filter comprising a member adapted for longitudinal vibration, said converter comprising a piezoelectric crystal and an associated inductor, said crystal having a length approximately equal to a half wave-length at said mid-band frequency and said crystal being free at one end and at its other end affixed to an end of said member.

11. A network in accordance with claim 10 in which said inductor is connected in series with said crystal.

12. A network in accordance with claim 10 in which said inductor is connected in shunt with said crystal.

13. A network in accordance with claim 10 in which said converter includes an added capacitor connected in shunt with said crystal.

14. A network in accordance with claim 10 in which said converter includes an added capacitor connected in shunt with said crystal, said inductor being connected in series with said crystal.

15. A network in accordance with claim 10 in which said converter includes an added capacitor connected in shunt with said crystal, said inductor also being connected in shunt with said crystal.

16. A network in accordance with claim 10 in which the mechanical image impedance of said converter substantially matches the image impedance of said mechanical filter.

17. A wave transmission network for transmitting a band of frequencies with a certain mid-band frequency while substantially attenuating frequencies falling outside of said band comprising a mechanical filter and an electromechanical converter, said mechanical filter comprising a member adapted for longitudinal vibration and a crossbar adapted to be set into flexural vibration by said member, said converter comprising a piezoelectric crystal and an associated inductor, said crystal having a length approximately equal to a half wave-length at said mid-band frequency, said crystal being free at one end and at its other end affixed to an end of said member and each half of said crossbar having a flexural antiresonance at a frequency near a limit of said band of frequencies.

18. A wave transmission network for transmitting a band of frequencies with a certain mid-band frequency while substantially attenuating frequencies falling outside of said band comprising a mechanical filter and an electromechanical converter, said mechanical filter comprising a member adapted for longitudinal vibration and two crossbars adapted to be set into flexural vibration by said member, said converter comprising a piezoelectric crystal and an associated inductor, said crystal having a length approximately equal to a half wave-length at said mid-band frequency, said crystal being free at one end and at its other end affixed to an end of said member, said crossbars being located close together near the center of said member, each half of one of said crossbars having a flexural antiresonance at a frequency near one limit of said band and each half of the other of said crossbars having a flexural antiresonance at a frequency near the other limit of said band.

19. An electromechanical device comprising a mechanical vibratory member and an electromechanical converter, said converter comprising a piezoelectric crystal and an associated inductor, said crystal having a length approximately equal to a half wave-length at a frequency to be converted and said crystal being free at one end and at its other end in mechanical association with said vibratory member.

20. A device in accordance with claim 19 in which the inductance of said inductor is proportional with respect to the electrical image impedance of said converter to provide a desired transmission band for said device.

21. A wave transmission network for transmitting a band of frequencies with a certain mid-band frequency comprising a mechanical filter and an electromechanical converter, said mechanical filter comprising a rod of acoustic material adapted for longitudinal vibration and a crossbar of acoustic material adapted to be set into flexural vibration by said rod, said crossbar being located near the center of said rod and having its dimensions so proportioned that the first clamped-free antiresonance of each half of said crossbar occurs at a frequency close to a limit of said band, said rod having a length approximately equal to a half wave-length at a frequency in said band, said converter comprising a piezoelectric crystal, said crystal having a length approximately equal to a half wave-length at said mid-band frequency and said crystal being free at one end and at its other end affixed to an end of said rod.

22. A network in accordance with claim 21 in which the band of frequencies transmitted by said converter substantially coincides with a band of frequencies transmitted by said filter.

23. A network in accordance with claim 21 in which said crystal is supported at a node of motion.

24. A network in accordance with claim 21 in which said converter includes an inductor connected in series with said crystal.

25. A network in accordance with claim 21 in which said converter includes an inductor connected in shunt with said crsytal.

26. A network in accordance with claim 21 in which said converter includes an inductor and a capacitor, said capacitor being connected in shunt with said crystal.

27. A network in accordance with claim 21 in which said rod has a length approximately equal to a half wave-length at the upper limit of said band and said antiresonance of each half of said crossbar occurs at a frequency close to the lower limit of said band.

28. A network in accordance with claim 21 in which said rod has a length approximately equal to a half wave-length at the lower limit of said band and said antiresonance of each half of said crossbar occurs at a frequency close to the upper limit of said band.

29. A network in accordance with claim 21 in which said mechanical filter includes a second crossbar similar to said first-mentioned crossbar, said second crossbar being located close to said first-mentioned crossbar and having its dimensions so proportioned that the first clamped-free flexural antiresonance of each half of said second crossbar occurs at a frequency close to the other limit of said band and said rod having a length approximately equal to a half wave-length at said mid-band frequency.

30. A mechanical wave filter for transmitting a band of frequencies comprising a rod and a crossbar both made of acoustic material, said crossbar being located near the center of said

rod, said rod having a length approximately equal to a half wave-length at a frequency in said band and said crossbar having its dimensions so proportioned that the first clamped-free flexural antiresonance of each half occurs at a frequency close to a limit of said band.

31. A filter in accordance with claim 30 in which the length of said rod is approximately equal to a half wave-length at the upper limiting frequency of said band and said flexural antiresonance occurs at a frequency close to the lower limit of said band.

32. A filter in accordance with claim 30 in which the length of said rod is approximately equal to a half wave-length at the lower limiting frequency of said band and said flexural antiresonance occurs at a frequency close to the upper limit of said band.

33. A filter, in accordance with claim 30, in which said rod and said crossbar are made of ceramic material.

34. A mechanical wave filter for transmitting a band of frequencies with a certain mid-band frequency comprising a rod and two crossbars all made of acoustic material, said crossbars being located close together near the center of said rod, said rod having a length approximately equal to a half wave-length at said mid-band frequency, one of said crossbars having its dimensions so proportioned that the first clamped-free antiresonance of each half occurs at a frequency close to one limit of said band and the other of said crossbars having its dimensions so proportioned that the first clamped-free antiresonance of each half occurs at a frequency close to the other limit of said band.

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