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R. B. BLACKMAN

2,091,250

WAVE FILTER

Filed Aug. 13, 1935

FIG. 1

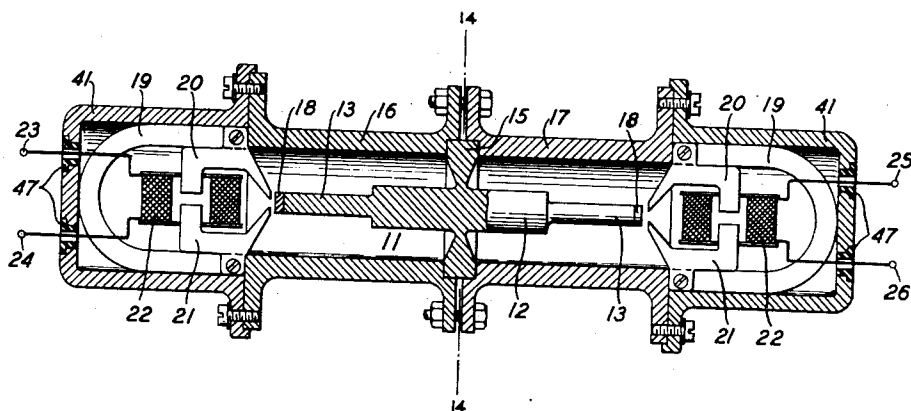


FIG. 2

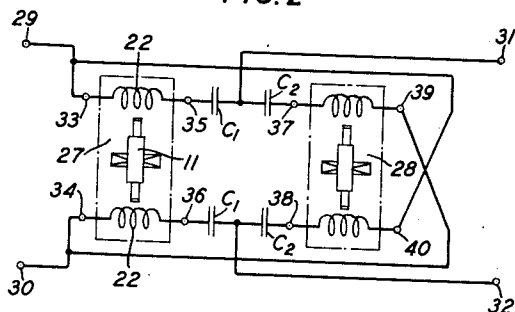


FIG. 5

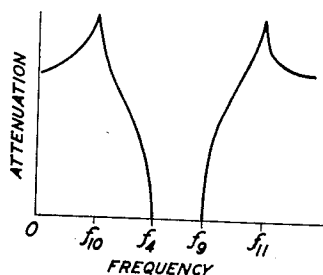


FIG. 3

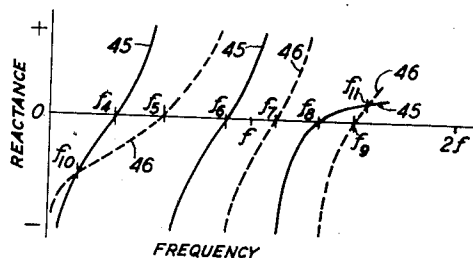
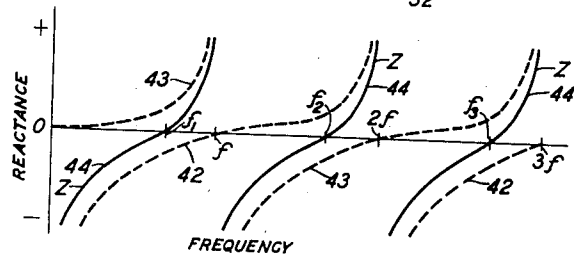


FIG. 4

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WAVE FILTER

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8 Claims. (Cl. 178—44)

This invention relates to impedance elements for use in wave filters and more particularly to impedance elements of the electromechanical type in which a mechanical vibrator coupled to an electrical circuit produces a reaction therein by virtue of its coupling thereto.

The principal object of the invention is to improve the efficiency and the frequency characteristics of electromechanical vibrators intended for operation at relatively high frequencies, for example the frequencies of carrier telephony. Another object is to improve and simplify the construction of mechanical vibratory systems having relatively complex resonance characteristics.

These objects are achieved by combining mechanical transmission lines, forming the mechanical vibratory portion of an electromechanical impedance, in such a way that wave reflection effects at their junction give rise to additional resonances at predetermined frequencies. By the use of structures particularly adapted to transmit longitudinal mechanical waves, either compressional or torsional, simple and rugged vibratory systems are made available for operation at the frequencies of carrier telephony and by utilizing materials, such as brass, aluminum or glass, which are characterized by extremely low dissipation, the efficiency of the vibratory system is greatly improved.

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

Fig. 1 is a view partly in section of one embodiment of the electromechanical impedance element of the invention;

Fig. 2 is a diagrammatic representation showing how two of the impedance elements of Fig. 1 may be utilized in a wave filter of the lattice type;

Fig. 3 shows reactance characteristics to which reference is made in explaining the invention;

Fig. 4 shows diagrammatically the reactance characteristics of the branches of the lattice network of Fig. 2; and

Fig. 5 is a diagram of a typical attenuation characteristic obtainable with the filter of Fig. 2.

Fig. 1 shows, partly in section, one embodiment of the electromechanical impedance element of the invention in which the mechanical vibrator 11 comprises a central portion 12 and two symmetrical end portions 13 having a cross-sectional area differing from that of the central portion. The cross-sections of these portions of the vibrator may be round or of any other convenient shape, and their areas and the lengths of the sections are proportioned to produce desired resonance characteristics. The vibrator is preferably made of non-magnetic material having

a low dissipation constant, such, for example, as brass, aluminum or glass. The vibrator is longitudinally symmetrical about a central plane represented by the line 14, 14 and when driven in the manner explained below it will have a nodal region coinciding with this plane of symmetry. In order to permit unrestricted vibration the vibrator is preferably supported at or near this nodal region. As shown in the figure, this may be done by means of a flange 15 which may be made an integral part of the mid-section 12. The flange may be clamped between the two parts 16 and 17 of the outer casing, or supported in any other suitable manner.

The vibrator is set into vibration by means of two similar electromagnetic drives, one being located at each end. Each of these drives comprises a magnetic armature 18, secured to the end of the vibrator, a permanent magnet 19, two pole-pieces 20 and 21 and a driving coil 22. The assembly is enclosed within the housing 41 and the lead wires to the coils are introduced through the insulating bushings 47. When oscillatory currents equal in magnitude but opposite in phase are impressed upon the two sets of coil terminals 23, 24 and 25, 26, respectively, mechanical forces of equal magnitude but of opposite phase are impressed upon opposite ends of the vibrator, and longitudinal compressional mechanical waves are produced therein.

Fig. 2 is a schematic diagram showing how two electromechanical impedances 27 and 28 of the type described above may be connected between a pair of input terminals 29 and 30, and a pair of output terminals 31 and 32 to form a band-pass wave filter of the symmetrical lattice type. The impedance 27 has terminals 33, 34, 35 and 36, and the impedance 28 has terminals 37, 38, 39 and 40, corresponding, respectively, to terminals 23, 25, 24 and 26 shown in Fig. 1. Each of the impedances is shown within a dotted enclosure, in the interest of clarity. The terminals 33 and 35 of the impedance 27 are connected between terminals 29 and 31, and the terminals 34 and 36 between terminals 30 and 32 to form the two series impedance branches of the lattice network. Similarly, terminals 40 and 38 of the impedance 28 are connected between terminals 29 and 32, and terminals 37 and 39 between terminals 31 and 30 to form the diagonal branches of the lattice network. In this way a single electromechanical impedance is made to provide a pair of impedance branches in the lattice. To equal capacitances C_1 , C_1 may be connected, respectively, in series with the terminals 35 and 36 and a second pair of equal capacitances C_2 , C_2 may be connected in series with the terminals 37 and 38 in order to improve the transmission characteristics of the filter, as explained hereinafter.

The nature of the impedance characteristic obtainable with this type of electromechanical impedance element will now be considered. The mechanical input impedance Z of a rod of non-uniform cross-section, such as the vibrator 11, when the driving forces at the two ends are in phase opposition is the same as that of a rod of the length of one of the end sections 13 connected in tandem with a rod of half the length of the mid-section 12, the latter being fixed at its distant end. If the vibrator is driven from one end only, a standing wave is set up thereon, and in general the central plane will be in motion. If now the driving force be removed from the first end and applied to the other end of the vibrator the same type of wave will be set up therein but the distribution of the motion will be inverted with respect to the central plane. However, if equal driving forces be applied to both ends simultaneously and in such a way that both of the armatures 13 are attracted or both are repelled at the same time the motion at the center due to the two forces will completely cancel out, leaving the central plane at rest, regardless of the frequency impressed upon the ends. Under these conditions the mechanical forces impressed upon the rod may be said to be in phase opposition.

It follows, therefore, that so far as the input impedance is concerned the vibrator may be considered to be fixed at its center. The impedance will be the same as that of a mechanical transmission line consisting of a section equal in length to the end section 13 in series with a second section of half the length of the central section 12, the latter being fixed at its distant end and consequently terminated in the equivalent of an infinite impedance. Following Equation (33) given on page 113 of Shea's "Transmission Networks and Wave Filters", published by D. Van Nostrand Company, the input impedance of such a system may be expressed as

$$Z = K_1 \frac{Z_r + K_1 \tanh P_1}{K_1 + Z_r \tanh P_1} \quad (1)$$

in which K_1 and P_1 are the characteristic impedance and transfer constant, respectively, of an end section 13, and Z_r is the terminating impedance of the end section. The characteristic impedance K and the transfer constant P of a rod, assuming that the elastic waves are propagated with a plane wave front normal to the axis, may be found from the following expressions:

$$K = A\sqrt{\rho E}$$

$$P = j\omega l \sqrt{\frac{\rho}{E}}$$

in which A represents the cross-sectional area, ρ is the density of the material, E is Young's modulus of elasticity, l is the length of the line and ω denotes the frequency multiplied by 2π .

Since the end section is connected in tandem with the mid-section, and the latter is effectively open-circuited at its distant end, the impedance Z_r is given by the equation

$$Z_r = \frac{K_2}{\tanh P_2} \quad (2)$$

in which K_2 and P_2 are the characteristic impedance and transfer constant, respectively, of half of the mid-section 12. Equation (2) is obtained by setting up an expression for the input impedance of the mid-section, similar in form to equation (1), and substituting therein the value of

the terminating impedance, which in this case is infinite in magnitude. Then by dividing both numerator and denominator by ∞ an expression for the impedance Z_r is obtained in the form given. Substituting in Equation (1) the value of Z_r given in Equation (2) gives

$$Z = K_1 \frac{\frac{K_2}{\tanh P_2} + K_1 \tanh P_1}{K_1 + \frac{K_2 \tanh P_1}{\tanh P_2}} \quad (3)$$

which, when numerator and denominator are divided by $\tanh P_1$, leads to the expression

$$Z = \frac{\frac{K_1 K_2}{\tanh P_1 \tanh P_2} + K_1^2}{\frac{K_1}{\tanh P_1} + \frac{K_2}{\tanh P_2}} \quad (4)$$

The impedance Z may be considered to be made up of the series connection of two impedances Z_1 and Z_2 corresponding to the two terms on the right-hand side of Equation (4). The first of these two impedances, corresponding to the first term, is

$$Z_1 = \frac{\frac{K_1}{\tanh P_1} \cdot \frac{K_2}{\tanh P_2}}{\frac{K_1}{\tanh P_1} + \frac{K_2}{\tanh P_2}} \quad (5)$$

which will be recognized as the impedance of two open-circuited, uniform transmission lines connected in parallel. When dissipation is neglected, such a transmission line is periodically resonant at some frequency f and at every odd multiple thereof, and is anti-resonant at zero frequency and every even multiple of f . In the special case where the two lines in parallel have the same transfer constants, that is, when $P_1 = P_2$, the critical frequencies of one will coincide with those of the other, and the combined impedance will be of the same form as the impedance of one alone. Such an impedance characteristic is shown by the dotted curve 42 of Fig. 3 for the frequency range from zero to $3f$.

The impedance Z_2 , corresponding to the second term, is

$$Z_2 = \frac{K_1^2}{\frac{K_1}{\tanh P_1} + \frac{K_2}{\tanh P_2}} \quad (6)$$

Multiplying both numerator and denominator by

$$\frac{K_1}{K_2} \tanh P_1 \tanh P_2 \text{ gives}$$

$$Z_2 = \frac{K_1 \tanh P_1 \cdot K_2 \left(\frac{K_1}{K_2}\right)^2 \tanh P_2}{K_1 \tanh P_1 + K_2 \left(\frac{K_1}{K_2}\right)^2 \tanh P_2} \quad (7)$$

This will be recognized as the parallel impedance of two short-circuited lines, one having the parameters K_1 and P_1 and the other having the parameters K_2 and P_2 , the latter being viewed through an ideal transformer having a turns ratio of K_1 to K_2 . A uniform transmission line short-circuited at its remote end will have anti-resonances at the frequency f and odd multiples thereof, and resonances at zero frequency and even multiples of f . If two such lines have equal transfer constants, their parallel impedance will have a reactance characteristic of the type shown by dotted curve 43 of Fig. 3.

The mechanical impedance Z of the vibrator 11, which, as explained above, may be considered to be made up of the two series impedances Z_1 and Z_2 , will therefore be the algebraic sum of the

two curves 42 and 43, and will be of the form shown by the solid line curve 44 of Fig. 3, having anti-resonances at the frequencies zero, f , $2f$ and $3f$, and resonances at the frequencies f_1 , f_2 and f_3 .

The armature 18, considered as a lumped mass, will not change the location of the anti-resonances but will cause each resonance to occur at a somewhat lower frequency. The magnetic field surrounding the armature exerts a force of attraction which increases more and more rapidly as the armature approaches the pole-pieces and is in effect a negative stiffness which will further lower each resonance frequency. The electrical impedance of the system at this point will be just the inverse of the mechanical impedance described above, resonances occurring where anti-resonances are located in the mechanical impedance, and vice versa. In this connection reference is made to United States Patent No. 1,642,506 to E. L. Norton issued September 13, 1927. The damped inductance of the driving coils 22, since they appear effectively as series elements, will cause each resonance to move down to a lower frequency but will not displace the anti-resonances. The addition of the capacitances C_1 or C_2 will move each resonance to a higher frequency and will introduce an anti-resonance at zero frequency. The resulting electrical impedance of the entire system is of the form shown by the solid line curve 45 of Fig. 4, having an anti-resonance at zero frequency, one at f_5 slightly below f and a third at f_7 slightly above f , and two resonances f_4 and f_6 falling below f and a third at f_8 between f and $2f$. The next anti-resonance, not shown on the diagram, will fall at a frequency at least as high as $3f_5$.

Curve 45 may represent, for example, the impedance of the element 27 of Fig. 2, in combination with the capacitances C_1 . A second electromechanical impedance, such as 28 of Fig. 2, with its associated capacitances C_2 , may be designed to have resonances at the frequencies f_5 , f_7 and f_8 , and anti-resonances at the frequencies zero, f_6 and f_9 , as shown by the dotted curve 46 of Fig. 4. Two such impedances may be arranged, as explained above in connection with Fig. 2, to form a lattice type band-pass wave filter. The transmission band will be located between the frequencies f_4 and f_9 where the two reactances are of opposite sign, and peaks of attenuation will occur at the frequencies f_{10} and f_{11} where the two curves cross each other. The transmission characteristic is shown diagrammatically by Fig. 5. Other attenuation peaks, not shown, may be located either above or below the transmission band.

The use of vibrators having non-uniform cross-sections, it will be noted, permits the building of wave filters having added resonances and anti-resonances occurring within the transmission band. These added critical frequencies may be utilized to broaden the transmission band and to introduce additional peaks of attenuation in the attenuating regions. Also, the use of material having a low dissipation constant reduces the loss and distortion in the transmission band and increases the height of the attenuation peaks.

What is claimed is:

1. In an electric wave filter, an electromechanical impedance comprising, as a mechanical vibratory element, a rod of elastic material longi-

tudinally symmetrical about its middle section, the material of said rod having a low dissipation constant and said rod comprising a plurality of portions of different cross-sectional areas the lengths and cross-sections of which are proportioned to produce a plurality of mechanical resonances located within the transmission band of said filter at frequencies unharmonically related to each other and relatively close together in order to broaden said band and increase the discrimination, means for supporting said rod at its middle section, similar electromagnetic driving means disposed at each end of said rod and adapted to produce longitudinal mechanical waves in said rod in response to oscillatory electric currents, and circuit connections between said driving means whereby the mechanical forces impressed on the opposite ends of said rod are equal in magnitude and opposite in phase.

2. In an electric wave filter an electromechanical impedance in accordance with claim 1 in which the electromagnetic driving means are adapted to produce longitudinal compressional waves in the driven rod.

3. In an electric wave filter, an electromechanical impedance in accordance with claim 1 in which the mechanical vibratory element comprises a rod of non-magnetic material and magnetic armatures at each end of said rod, said armatures forming part of the said electromagnetic driving means and being disposed to produce longitudinal compressional waves in said rod.

4. An electromechanical impedance in accordance with claim 1 in which the mechanical vibratory means comprise a rod of non-magnetic metal and in which the supporting means for said rod comprise a flange integral with said rod at the mid-section thereof.

5. In an electric wave filter, an electromechanical impedance comprising, as a mechanical vibratory element, a rod of non-magnetic elastic material longitudinally symmetrical about its middle section, said rod comprising a plurality of portions of different cross-sectional areas the lengths and cross-sections of which are proportioned to produce a plurality of mechanical resonances located within the transmission band of said filters at frequencies unharmonically related to each other and relatively close together in order to broaden said band and increase the discrimination, means for supporting said rod at its middle section, similar electromagnetic driving means disposed at each end of said rod and adapted to produce longitudinal mechanical waves in said rod in response to oscillatory electric currents, and circuit connections whereby said driving means are adapted to impress forces of opposite phase on said rod.

6. An electromechanical impedance in accordance with claim 5 in which the said electromagnetic driving means are adapted to produce longitudinal compressional waves in said rod.

7. An electromechanical impedance in accordance with claim 5 in which the several portions of the said rod are of like cross-sectional form and are of equal length.

8. An electromechanical impedance in accordance with claim 5 in which the several portions of the said rod are of circular cross-section and are of equal lengths.

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