July 4, 1939. H. G. OCH 2,164,541

ELECTROMECHANICAL WAVE FILTER

Filed May 14, 1938

FIG. 1

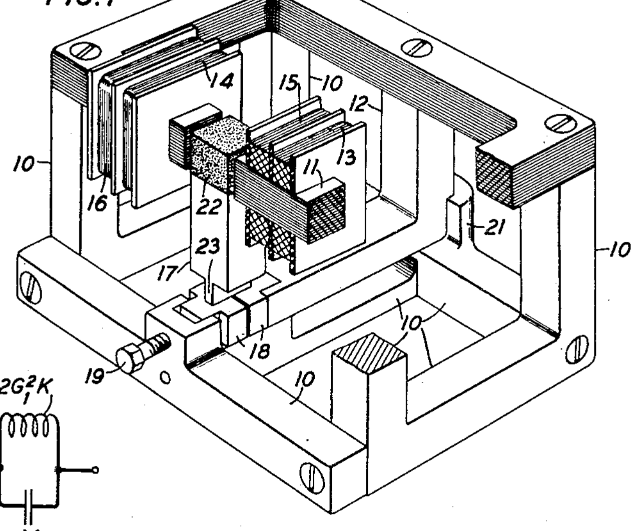


FIG. 3

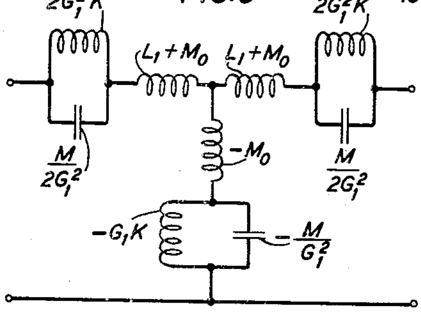


FIG. 2

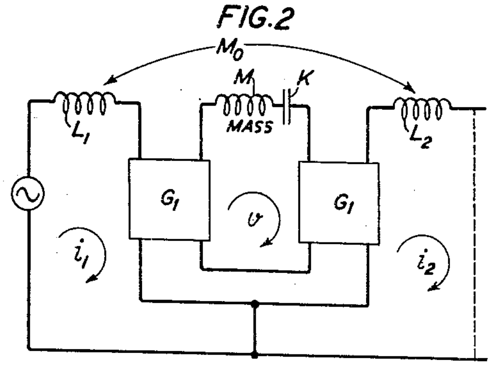


FIG. 5

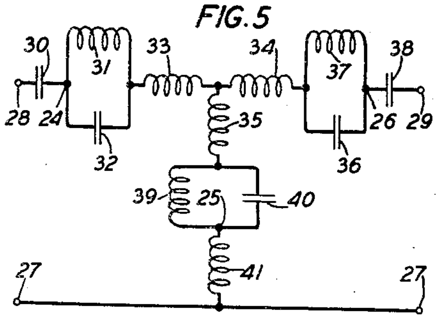


FIG. 4

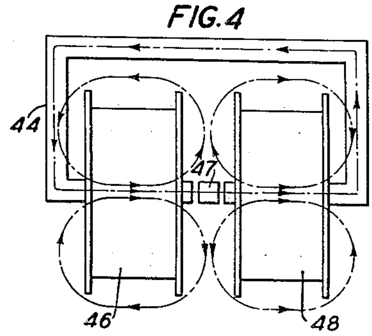
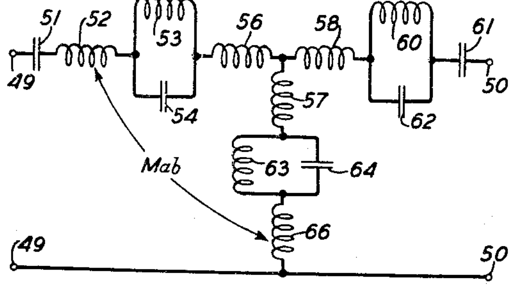


FIG. 6



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ELECTROMECHANICAL WAVE FILTER

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4 Claims. (Cl. 178—44)

This invention relates to improvements in electro-mechanical wave filters.

An object of the invention is to improve the efficiency of such filters.

A further object is to provide more economical means for eliminating the effect of unwanted mutual inductance between the coils of such a filter and providing an appropriate termination at one end for parallel operation with filters transmitting adjacent frequency bands.

Another object is to reduce the leakage flux between the coils of such a filter and thus eliminate the resulting dissipation of energy.

Other and further objects will become apparent during the course of the following description.

This invention is directed to electromechanical filters of the general types illustrated in the copending application of E. Lakatos, Serial No. 101,061, filed September 16, 1936, and particularly of the type employing essentially the structure illustrated in Fig. 3 of that application. In this latter type of electromechanical filter it has been found that objectionable dissipation results from the leakage of flux between the two coils of the device. In accordance with the present invention the coils are divided into equal parts and corresponding parts of the two coils are assembled adjacent to each other so that leakage of flux is substantially eliminated.

An additional feature of this invention is its applicability to the situation where the transmission characteristics desired require that the mutual inductance of the windings be annulled and in addition that one end of the filter be "X" terminated for parallel operation with one or more similar filters passing adjacent frequency bands. The advantages resulting from employing "X" terminations for wave filters for parallel operation are explained in U. S. Patent 1,557,230, issued October 13, 1925, to O. J. Zobel. As is well known to the art "X-termination" consists in changing the terminating arm of the network so that its impedance is a particular fractional part of the normal impedance of a corresponding full arm of the network being terminated. For example, if a network has a full series arm impedance of Z_1, it would be X terminated by a series arm having an inductance of XZ_1, X being a fraction less than unity. The value of X is chosen in accordance with principles described at length in the above-mentioned patent to Zobel.

While each of the above-described requirements could be satisfied by employing two independent retardation coils, one to annul the unwanted mutual and the other to provide the desired fractional termination of the filter, it is possible in accordance with the present invention to employ a single coil having two windings on a common core to accomplish both results. As the cost of such a coil or transformer is only slightly more than that of a single retardation coil, an appreciable economy is thereby effected.

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

Fig. 1 shows the assembly of an electromechanical filter of this invention with portions of the coils, core and supporting frame broken away to show the construction more clearly;

Fig. 2 shows in diagrammatic form an equivalent network of a filter of the type illustrated in Fig. 1;

Fig. 3 shows in schematic form an equivalent electrical network of the device of Fig. 1;

Fig. 4 is illustrative of the magnetic flux paths established if the coils are not subdivided and corresponding sections mounted adjacently in the manner indicated in Fig. 1;

Fig. 5 shows in schematic form a combination of the device of Fig. 1 with additional series condensers and a shunt coil to widen and improve the transmission band of the electromechanical filter of Fig. 1; and

Fig. 6 is illustrative of the further feature of this invention whereby with a single auxiliary two-winding coil the combination of Fig. 5 may be given an X-termination and at the same time the mutual inductance between the filter coils themselves may be annulled.

In detail, with particular reference to Fig. 1, the electromechanical portions of filters of this invention may comprise a frame of non-magnetic material 10, arranged to support a core of magnetic material 11 of low reluctance to alternating flux, having a single small gap in which the end of an armature piece 17 may vibrate. Armature 17 is supported on spring member 23 which in turn is clamped between the halves of block 18. An L-shaped permanent magnet 12, one end being keyed to fit block 18, and the other drilled and threaded to be joined firmly to the center of the rear side of core 11, is supported at its elbow by a projection 21 of frame 10 and block 18 is clamped against magnet 12 by screw 19.

By virtue of this arrangement the steady flux of permanent magnet 12 passes through the left half of core 11 in the opposite direction from that in which it passes through the right half of core 11. The distribution of direct flux to the two halves of core 11 obviously depends upon the position of the armature and varies in accordance with changes in position resulting from vibration of the mechanical vibrating system. The permanent magnet 12 having high reluctance to alternating flux, does not sensibly reduce the alternating flux flowing through core 11. Core 11 is laminated to eliminate eddy current losses and the tip 22 of armature 17 may, for the same reason, be of suitable compressed powdered magnetic material, the particles being insulated by lacquer or other suitable binding material.

As explained in United States Patent 2,115,818 to E. Lakatos, issued May 3, 1938, an electromechanical device such as that of Fig. 1 in which an electrical input circuit is coupled through a simple mechanical vibratory system to an electrical output circuit, may be represented diagrammatically as indicated in Fig. 2 of this application. (Refer particularly to Fig. 13 of United States Patent 2,115,818 to Lakatos where, omitting the electrical condensers S_1 and S_2, the structure contemplated is shown.)

In Fig. 2, L_1 represents the input winding comprising half windings 13 and 14 of Fig. 1, L_2 represents the output winding comprising half windings 15 and 16 of Fig. 1, M_0 represents the electromagnetic coupling between these windings, G_1 represents the force factor which provides the respective electromagnetic couplings between the mechanical vibratory system and the above-mentioned windings L_1 and L_2, and mass M and stiffness K represent the mass and stiffness respectively of the bar armature 17 of Fig. 1 and the spring 23 of Fig. 1, comprising the mechanical vibratory system.

Assuming that the device of Fig. 1 is substantially symmetrical about a vertical plane which longitudinally bisects the permanent magnet 12 and that the input and output windings are equal (that is, that in Fig. 2, inductance L_1 may be considered equal to inductance L_2) and the force factor coupling L_1 to the vibratory system may be considered equal to the force factor coupling L_2 thereto, we may write the following mesh equations for the structure of Fig. 2.

$$E=i_1pL_1+i_2pM_0+G_1v \qquad (1)$$

$$o=-G_1(i_1+i_2)+v\left(pM+\frac{1}{pK}\right) \qquad (2)$$

$$o=i_2pL_1+i_1pM_0+G_1v \qquad (3)$$

where $p=j2\pi f$, i_1 and i_2 are the respective mesh currents of the input and output circuits and v is the velocity of the vibrating member; from (2)

$$v=\frac{G_1(i_1+i_2)}{pM+\frac{1}{pK}} \qquad (4)$$

whence (1) and (3) become

$$E=i_1pL_1+i_2pM_0+\frac{G_1^2(i_1+i_2)}{pM+\frac{1}{pK}} \qquad (5)$$

$$o=i_2pL_1+i_1pM_0+\frac{G_1^2(i_1+i_2)}{pM+\frac{1}{pK}} \qquad (6)$$

Equations (5) and (6) may obviously be represented by a two-mesh electrical network, as shown in Fig. 3, from which it is evident that the structure of Fig. 1 may be represented by a simple T-network of inductances as shown in Fig. 3 in terms of the self-inductance L_1 and mutual inductance M_0 of Fig. 2 and an anti-resonant combination in each arm of the network as shown in Fig. 3 in terms of the force factor G_1, the mass M and the stiffness K of Fig. 2.

In the series arms the anti-resonant combinations represent the respective reactions upon the coils L_1 and L_2 of the vibrating system and the anti-resonant combination in the shunt arm represents the coupling between coils L_1 and L_2 which is afforded by the vibrating system.

The elements of the equivalent network representing the coupling between the input and output coils are conventionally represented as negative and an electrical network as illustrated in Fig. 3 would have the same transmission, phase and impedance characteristics as the device of Fig. 1 employing the winding comprising sections 13 and 14 connected in series aiding as the input and the winding comprising sections 15 and 16 connected in series aiding as the output. Physically the two windings of Fig. 1 (each comprising two sections as described in detail above) are connected in series aiding also and the junction between the two windings is employed as the third or ground terminal of the T-network.

The reason for dividing the input and output windings of the device of Fig. 1 into halves and assembling half of each winding on each side of the air-gap is apparent from the diagram of Fig. 4 which represents the flux paths which would obtain were the coils not subdivided. In Fig. 4, coils 46 and 48 are assembled on core 44, the coils being on opposite sides of an air-gap in which an armature 47 is disposed. It is obvious that appreciable flux from each of coils 46 and 48 would not thread the other coil because of the intervening air-gap but would be merely what is commonly termed stray flux and is accompanied by loss of energy and efficiency.

The structure of Fig. 3 is by inspection in the light of well-known filter design theory, a band-pass wave filter. Upon closer inspection, however, it is found that only a relatively narrow band of frequencies may be passed through a filter having the configuration of Fig. 3 unless the inductance $-M_0$ of the shunt arm is effectively removed. Since it is negative it may be removed by placing effectively in series with it an equal positive inductance. The transmission characteristics of the filter may be still further improved by adding in each series arm a series condenser.

These additions may be effected by the use of auxiliary electrical elements and lead to a combination having an equivalent electrical network as shown in Fig. 5.

Physically the combination indicated in Fig. 5 consists of a device, as illustrated in Fig. 1, two auxiliary condensers and one auxiliary inductance coil, the latter three elements being of any convenient conventional design. These auxiliary elements may conveniently be mounted on a common base with the device of Fig. 1. The two windings of the device of Fig. 1 are, as described above, connected in series aiding. The auxiliary inductance coil, being designed to annul the mutual inductance between these two windings, must be connected at one terminal to the junction between them. The free terminal of the auxiliary coil then becomes the third or ground terminal of the T-network. Inductance 41 represents this auxiliary coil and terminals 27 represent the ground terminal in Fig. 5. The free terminals of the windings of the device of Fig. 1 are then connected to the two auxiliary condensers represented by capacities **30** and **38**, respectively, of Fig. 5. The free terminals of the auxiliary condensers then become the input and output terminals, respectively, of the T-network represented by terminals **28** and **29** of Fig. 5. This combination may in accordance with well-known filter theory provide a wide band wave filter.

If a wave filter having an equivalent electrical network, as shown in Fig. 5, is to be connected at one end in parallel with a similar filter or filters transmitting adjacent frequency bands, the final arm of the network should, as described in the above-mentioned patent to O. J. Zobel, be given a particular fractional portion of the normal full arm impedance. This is commonly known as X-termination of the filter.

For the network of Fig. 5, assuming it is desired to operate it in parallel with one or more similar filters at the terminals **28** and **27**, it will be necessary to modify condenser **30** and to add an auxiliary inductance coil in series therewith. It should be noted that inductance **33** of Fig. 5 is contributed by the input winding of the device of Fig. 1, and this winding may not be altered without effectively changing the impedance of the output circuit, because the input and output windings are electromagnetically coupled. However, one auxiliary inductance coil is already required to provide the inductance **41** employed in the shunt arm as described above. By design in accordance with the following formulae, the inductance required to provide the desired X-termination may be obtained from the same auxiliary inductance coil as is employed to furnish inductance **41**. The two are, in effect, built into a transformer, the two windings of which furnish the desired auxiliary inductances for their respective arms of the filter network and the mutual between the two windings of this auxiliary coil is taken care of by reproportioning the other elements of the filter. By this means the use and substantially the entire cost of a second independent auxiliary inductance coil may be avoided, since an auxiliary two-winding coil of the type contemplated may be constructed at only slightly greater cost than a single-winding coil. This leads to the combination represented by the equivalent electrical network of Fig. 6. The auxiliary two-winding coil above mentioned is represented in the schematic diagram of Fig. 6 by inductances **52** and **66** coupled by mutual inductance M_{ab}.

The formulae employed in the conversion are as follows:

$$L_1=\frac{Z_0}{2\pi(f_2-f_1)} \qquad (7)$$

$$C_1=\frac{(f_2-f_1)}{2\pi f_m^2 Z_0} \qquad (8)$$

$$L_2=\frac{(f_2-f_1)Z_0}{2\pi f_m^2} \qquad (9)$$

$$C_2=\frac{1}{2\pi(f_2-f_1)Z_0} \qquad (10)$$

$$C_a=\frac{C_1}{2X} \qquad (11)$$

$$C_b=C_1 \qquad (12)$$

$$M=\frac{2G_1^2C_2}{10^9} \qquad (13)$$

$$K=\frac{10^9L_2}{2G_1^2} \qquad (14)$$

$$(1+M_0)L_0+L_a+M_{ab}\sqrt{L_aL_b}=2XL_1 \qquad (15)$$

$$(1+M_0)L_0-M_{ab}\sqrt{L_aL_b}=L_1 \qquad (16)$$

$$-M_0L_0+L_b+M_{ab}\sqrt{L_aL_b}=0 \qquad (17)$$

In the above equations, L_1 is the inductance and C_1 is the capacity required in a mid-series arm

$$\left(\frac{Z_1}{2}\right)$$

comprising a series resonant combination of a coil and a condenser, for a confluent band filter having the desired band width, frequency location and impedance. These elements, as is well known in the art, are defined in terms of the characteristic impedance Z_0, the cut-off frequencies f_1 and f_2 and the mid-band frequency f_m.

Similarly L_2 is the inductance and C_2 is the capacity required in a mid-shunt arm ($2Z_2$) comprising a parallel anti-resonant combination of a coil and a condenser, for a confluent band filter having the same desired band width, frequency location and impedance. These elements are also defined in terms of Z_0, f_1, f_2 and f_m.

C_a of Equation (11) represents the modification required for the series condenser in the input arm of the filter to contribute toward the attainment of the desired X-termination, as described in the above-mentioned patent to Zobel. In the equivalent electrical circuit of Fig. 6, C_a is condenser **51**.

C_b is condenser **61** in the output series arm of Fig. 6.

M of Equation (13) is the effective mass of the vibrating reed at the center of the air-gap. G_1 is the force factor expressing the coupling between the reed and the electrical coils of the system.

K of Equation (14) is the effective compliance of the reed.

L_0 of Equations (15 to 17), inclusive, is the total inductance of each of the full windings (input and output) of the assembly of Fig. 1.

M_0 is the coupling between the input and output windings of Fig. 1. L_a and L_b are the self-inductances of the two compensating coil windings of the above-mentioned auxiliary two-winding coil represented by inductances **52** and **66**, respectively, in the diagram of Fig. 6 and M_{ab} is the coupling between these two windings.

By way of example, for an experimental combination of the nature contemplated in Fig. 6 designed in accordance with the principles of this invention, the values of the above items were approximately as follows:

Z_0=600 ohms
f_m=1275 cycles per second
f_2-f_1=110 cycles per second
L_1=.868 henries
C_1=.0180 microfarads
L_2=.00657 henries
C_2=2.41 microfarads
C_a=.0112 microfarads
C_b=.0180 microfarads
G_1=3.34 x 10^7 dynes
M=5.38 grams
K=.00290 centimeters per dyne
M_0=90 per cent
M_{ab}=98 per cent
L_0=.561 henries
L_a=.132 henries
L_b=.307 henries.

The physical dimensions of the magnetic core were, approximately, length 2⅞ inches, breadth 1¼ inches, cross-sectional area .063 square inch, length of air-gap .288 inch. It was made of an alloy comprising approximately 80 per cent nickel, 4 per cent molybdenum and the balance iron. The reed was of cold rolled steel ¼ by ¼ by1⅛ inches, except for its tip, in the air-gap, which was of "insulated powder" of the alloy employed for the core. The tips' dimensions were ¼ by ¼ by $\frac{5}{16}$ inch. The spring was of cold rolled steel and its dimensions were ¼ inch wide by ⅛ inch high by .105 inch thick.

The permanent magnet was of a steel alloy comprising approximately 36 per cent cobalt, 7 per cent tungsten, 4 per cent chromium, .6 to .8 per cent carbon and the balance iron, and was magnetized to saturation in place. Its cross-section was .263 square inch.

Each half of the input and output windings, respectively, comprised 1300 turns of number 29 wire. The auxiliary two-winding coil, represented in the schematic diagram of Fig. 6 by inductances **52** and **66** coupled by mutual inductance M_{ab} as mentioned above, comprised windings of 1250 turns of number 34 wire and 1900 turns of number 34 wire, respectively, on a toroidal core of "insulated powder" of the alloy employed for the reed tip as above described. The coil core was of .075 square inch cross-section and 1.13 inches mean diameter.

Numerous applications of the principles of this invention will occur to those skilled in the art. No attempt has here been made to be exhaustive. The scope of the invention is defined in the following claims.

What is claimed is:

1. An electromechanical transducer comprising a mechanical vibratory member, a magnetic core of low reluctance to alternating flux providing an air-gap in which one end of said vibratory member is positioned, a source of direct magnetomotive force associated with said vibratory member, a magnetic path of low reluctance to direct flux including said source of direct magnetomotive force and connecting said vibratory member and the magnetic mid-point of said core, and an input winding and an output winding assembled on said core, said windings being connected in series aiding and the point of junction between the said input and output windings being connected to the grounded side of the transducer circuit, each of said windings being subdivided into a plurality of parts connected in series, the parts of one winding being electrically balanced with corresponding parts of the other winding, said corresponding parts of the two windings being mounted on said core adjacent to each other whereby leakage flux between the two windings is substantially eliminated and the efficiency of said transducer is increased.

2. In combination, an electromechanical transducer as defined in claim 1 and an electrical transformer having two windings, one of said windings being connected in series with the transducer input and the other between the point of junction of the input and output windings and the grounded side of the transducer circuit, the self-inductances of the windings of said transformer and the mutual inductance between them being so adjusted that the mutual inductance between the transducer input and output windings is effectively annulled and at the same time the input impedance of the transducer is modified for more efficient parallel operation with electrically similar transducers passing frequency bands adjacent to that passed by the combination of this claim.

3. An electromechanical transducer as in claim 1, the end of the vibratory member positioned in the air-gap of the core being made of particles of magnetic material bound together by an insulating binding material whereby eddy currents will not be established therein by the alternating flux and increased efficiency of the transducer is obtained.

4. An electromechanical wave filter comprising a magnetic core of low reluctance to alternating current flux, said core having an air-gap therein, an input winding and an output winding, said input and said output windings being disposed on said core, a half of each of said windings being disposed on each side of the said air-gap in said core, means for introducing direct flux into said core, said means comprising a source of direct flux and a frequency-selective mechanical vibratory system, a portion of said vibratory system being disposed in said air-gap, said vibratory system being responsive to alternating flux within a desired range of frequencies whereby when alternating currents within said desired range of frequencies are introduced into said input winding said vibrating system will respond and cause variations in the said direct flux in said core corresponding to said alternating input currents.

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