Oct. 27, 1942. R. A. SYKES 2,300,075

PIEZOELECTRIC CRYSTAL CONTROLLED OSCILLATOR

Filed July 25, 1941

FIG. 1

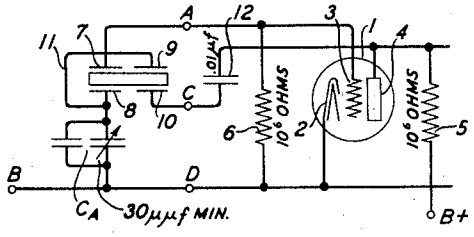


FIG. 2

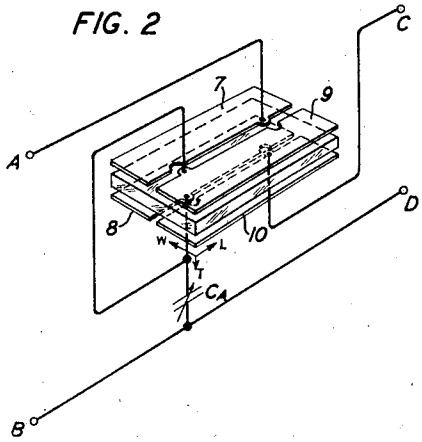


FIG. 3

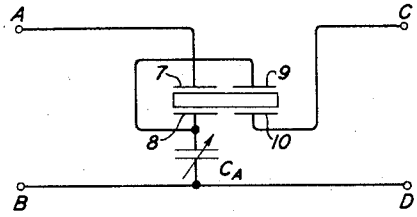


FIG. 4

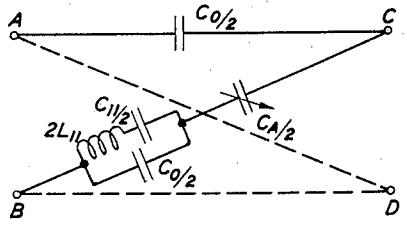
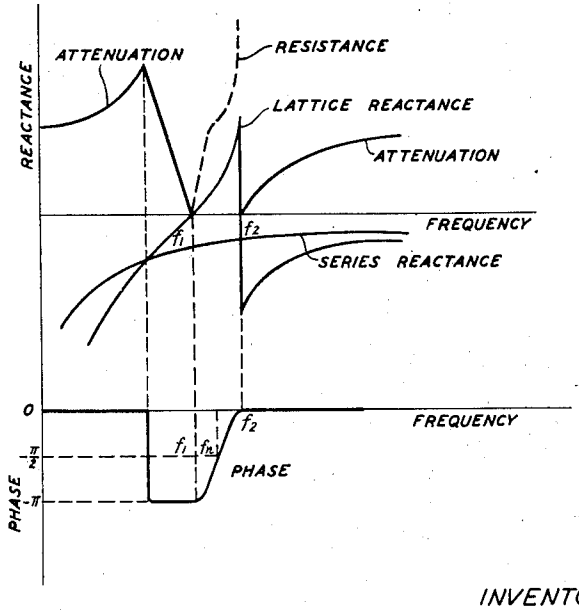


FIG. 5



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PIEZOELECTRIC CRYSTAL CONTROLLED OSCILLATOR

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Application July 25, 1941, Serial No. 403,979

6 Claims. (Cl. 250—36)

This invention relates to a piezoelectric crystal-controlled oscillator and especially as pertaining to the piezoelectric crystal and its immediately associated circuits. In particular the oscillator in question is adapted to generate relatively low frequency oscillations and accordingly utilizes a piezoelectric crystal adapted to vibrate flexurally.

It is an object of the invention to achieve an improved form of crystal controlled oscillator as adapted to generate oscillations of a relatively low order of frequency as compared with conventional crystal-controlled frequencies.

Since, at the imputed order of frequency, namely a frequency of a few kilocycles per second, a crystal is most effectively used when so organized with respect to its electrodes and immediately associated circuits as to vibrate flexurally, it is a second object of the invention to improve the function of flexurally vibratable piezoelectric crystals as included in an oscillation generating system.

A more specific object of the invention is to provide, in a generating system conforming with the above objects, a simple and effective means for slightly varying the characteristic frequency of the generated oscillations.

The invention is expressed in a crystal controlled oscillator utilizing a piezoelectric crystal (hereinafter to be denominated merely as "crystal") in the feedback path from the output electrodes to the input electrodes of an electron discharge amplifier and therefore adapted to determine and control the frequency of the generated wave, the crystal being adapted, by the employment of two pairs of electrodes so physically arranged and electrically conditioned as to relative potentials and signs of potential to cause the crystal to vibrate flexurally. The means for causing the crystal to vibrate flexurally follows the teachings of U. S. patent to Marrison 1,823,329, September 15, 1931, in which see Fig. 8, the difference resulting only from the fact that the Marrison crystal is a part of a two-terminal network whereas the crystal organization of this invention constitutes a part of what is effectively a four-terminal network, a pair of individual terminals being specific to each of the corresponding pairs of terminals of the associated vacuum tube, namely the input and output electrodes, to which, as is customary, one electrode, namely the cathode, is common.

The principal novel feature of the invention has to do with a specific form of organization as above in which the two crystal circuits, corresponding to the two pairs of network terminals coalesce to enable them to be joined to the corresponding common terminal of the vacuum tube. In particular, the resulting common terminal of the crystal network is separated from the corresponding common terminal of the vacuum tube by a common cathode circuit which includes a variable capacitor. A capacitor (condenser) in this position provides a means for changing the coupling, in the resultant combination, between the effective component two-electrode crystals or lattice networks, and therefore for slightly changing the resonant frequencies thereof and consequently the characteristic frequency of the resultant flexural vibrations, all consistently with a very high degree of frequency stability as effected by variations of circuit constants and the like.

The invention therefore makes possible the realization of crystal control of an oscillator where the crystal is conditioned to vibrate flexurally and under conditions of relatively great frequency stability. Since the frequency of said flexural vibrations may be as low as about 4 kilocycles, which is very much lower than the conventional frequency range of a crystal as used when vibrating in its more conventional modes, the invention may be thought of as a means for effectively using a crystal in a subnormal frequency range, or as extending the frequency range of a crystal downwardly into a range not heretofore practicable where great frequency stability is required. The oscillator of the invention might be thought of, on account of its superior qualities as to frequency stability, as providing a frequency substandard at this low range, utilizing the inherently superior qualities of a crystal heretofore realized only in a higher range. This low range is of importance in certain specific fields, as in frequency modulation transmission and in coaxial cable transmission.

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

Fig. 1 illustrates a crystal-controlled oscillator of the invention;

Fig. 2 illustrates, in a manner not capable of disclosure in Fig. 1, the specific relationship of the electrodes to the crystal and the connections of the same to the associated circuit;

Figs. 3 and 4 illustrate the network theory pertaining to the crystal organization of the invention; and

Fig. 5 graphically illustrates certain electrical characteristics of the network of Figs. 3 and 4.

In Fig. 1 the crystal network together with associated capacitor C_A, on account of which the circuit as a whole possesses unique characteristics and in which the invention to a large extent inheres, is represented as a four-terminal network, the terminals being indicated at points A, B, C and D. In the other figures illustrating this network, the character of the crystal-capacitor combination as a four-terminal network will be more plainly evident. In such other figures the termini will be similarly labeled. This network is related to electron discharge device **1** comprising the usual cathode **2**, control electrode **3** and anode or plate **4**, which last-named element is energized from the positive terminal of the battery indicated by B+ through resistance **5** The grid, that is control electrode, has a negative bias as achieved by resistance **6** connected between it and the cathode, although other conventional biasing means could be used.

The crystal network provides the feedback between the output electrodes of the tube, comprising the plate and cathode, and the input electrodes of the tube comprising the grid and cathode, the network being connected effectively to the output electrodes of the tube at terminals C and D and to the input electrodes of the tube similarly at terminals A and B. The reference letter B is used just above in place of D, which is the obvious equivalent, only in deference to the treatment of the network as a four-terminal network instead of a three-terminal network as will be more evident from the consideration of Figs. 3 and 4. The capacitor **12** is in the circuit between the network and the output electrode **4**. It serves only as a blocking condenser in view of the plate energizing source which otherwise would have a potential directly impressed on a crystal electrode. The frequency adjusting capacitor C_A, which, as disclosed, may in a practical case be an organization made up of a fixed and a variable capacitor in parallel, is in a portion of the circuit which is common to the input and output circuits of the device and therefore in common to the two interelectrode circuit paths through the crystal corresponding to the respective pairs of network terminals. The capacitance of the fixed capacitor should be sufficient to prevent the oscillations from ceasing when the variable capacitance is a minimum. In a practical instance it was, as shown, about 30 $\mu\mu$f. minimum.

The crystal is shown in end view in this Fig. 1. It comprises the electrodes **7** and **8** applied to the opposite principal faces of the crystal near one edge thereof and extending in the direction of the length of the crystal. Electrodes **9** and **10** are similarly applied near the opposite edge of the crystal. The electrodes **8** and **9** are interconnected by leads **11** as shown. The mechanical and electrical design of the crystal organization, having to do also with the interrelations of the pairs of electrodes and of them and the circuits of the electric discharge device, is such as to induce flexural vibrations in the crystal. This is evident from the analogy between this crystal and the crystal of United States patent to Marrison 1,823,329, September 15, 1931, in which see especially Fig. 8 thereof. The essential difference is that Marrison employs a crystal organization which is essentially a two-terminal network as against the effective four-terminal network of the present circuit. It is evident that there is a reversal of direction of stress through the crystal in comparing the effect of one pair of electrodes to that of the other pair of electrodes. Therefore, there will be a longitudinal displacement along the length of the crystal individual to one pair of electrodes which is opposite in sign to the corresponding longitudinal displacement individual to the other pair of electrodes. The result is that flexural vibrations are induced in the direction of the crystal width, that is, with respect to Fig. 1, in the plane of the sheet and in a horizontal direction therein.

A crystal well adapted for the purposes of the invention, as demonstrated by experiment, is that known to the assignee corporation as having the MT cut, which is shown and described in W. P. Mason Patent 2,282,369, issued May 12, 1942, which patent also shows a practicable method of mounting the crystal. The frequency of such a crystal for long thin bars, as in the instant case, is given approximately by the equation

$$f = 580 \frac{W}{L^2} \text{ kilocycles}$$

where W and L are respectively the width and length of the crystal expressed in centimeters. In a typical crystal which was found suitable, the frequency was 5,269.75 cycles per second at 24° centigrade and with a length, width and thickness of 66.3, 4.65 and 1.00 millimeters, respectively. The electrical specifications of the remaining important elements of the oscillator circuits, in the instance of the same test oscillator, are as represented on Fig. 1.

Fig. 2 illustrates the crystal in perspective and indicates better than by the above description how the electrodes are related to the crystal and to their associated electrical circuits. The crystal is plated in the usual manner and divided along the length to give four electrodes as shown. Connections as well as mechanical shock-proof mounting is obtained by soldering spring steel wires to the plated areas of the crystal. In a particular instance .005 inch spring steel wires were used. Fig. 2 shows how the electrodes are arranged to allow the connections to be on the neutral axis of vibration and along the medial axis of extension. The distance from the ends of the crystal to the connections should be .224 of the total crystal length.

Fig. 3 shows the crystal of Fig. 1 in a manner more nearly conventionalized for the purpose of circuit analysis, Fig. 4 which will be treated later representing the equivalent electrical circuit.

A crystal of the type used, and which would well serve the purposes of the circuit of this invention, had an extremely low temperature coefficient of frequency as a result of the particular angles of cut used. Although there was some variation in frequency with temperature, it was nearly zero at about 5° to 10° centigrade. The organization as adapted for operation showed a variation in frequency of less than one part in a million with changes in load or supply voltage to the tube of the order of 50 per cent. It was a logical conclusion that if the oscillator supply voltage could be maintained to an accuracy of 1 per cent and the temperature of the crystal could be controlled to .1° centigrade, this type of oscillator, as demonstrated, should maintain its frequency to about one part in a million. Assuming no temperature control but ordinary ranges of 20° to 40° centigrade, the variation should not exceed ±15 parts per million.

Fig. 4 illustrates the equivalent electrical cir-

cuit of the crystal network (including the frequency control capacitor C_A) of Figs. 1 to 3, in terms of the corresponding electrical values for a two-electrode crystal having the same electrode coverage as the two electrodes on each face of the present considered crystal. The representation of such a two-electrode crystal would be like that of either of the lattice arms of Fig. 4 and the inductance L_{11} and capacitances C_{11} and C_0, positioned as shown in the lattice of Fig. 4, may be assumed to have unit values. Fig. 4 shows that the flexural vibrating crystal of the invention may be represented by a four-terminal lattice network in which each lattice arm comprises an inductance-capacitance organization like that of the two-electrode crystal but with double the value of inductance and half the value of capacitance in each instance, this organization being connected in series with a capacitor having a capacitance equal to one half of the capacitance of capacitor C_A. The series arms are each made up of a capacitor having a capacitance equal to one half of C_0, that is one half of the shunt capacitance of the equivalent two-electrode crystal.

It is the principal purpose of Fig. 4 to show that, in the equivalent circuit, the capacitance corresponding to capacitor C_A, appears only in the lattice arms of the equivalent network (filter) and therefore does not appear in the series arms. This capacitor therefore provides an effective way, by use of what amounts to a single variable element, to change the coupling of the resulting combination or resonant frequency of the lattice arms. The effect of such capacitor C_A, as changing the coupling rather than functioning merely analogously as a series trimming capacitor of the usual two-electrode crystal, makes possible its great utility in slightly changing the frequency of the resultant oscillations, similarly as the same ultimate function may be achieved by a trimming capacitor as used with said two-electrode crystals.

The principal use of C_A is, of course, to provide an adjustment of ± 30 cycles per million, for example, which is the most advantageous way of shifting the resonant frequency of this crystal. Since this crystal oscillates at substantially its resonant frequency a series capacitance must be used. Any other position for the series capacitance would introduce considerable ground capacitance and also would raise the over-all impedance of the equivalent lattice network, a detrimental factor for low frequencies.

The attenuation, phase, and other characteristics of the network of Fig. 4 are shown in Fig. 5. These curves, for simplicity, represent the conditions for one lattice arm and one series arm as shown in full lines in Fig. 4. Of course, considering the network as a filter, such filter would be of the single mesh type and therefore would depart considerably from the ideal case where there would be assumed an infinite reiteration of said meshes or sections with provision for complete absorption, and therefore absence of reflection, from the remote end. To that extent the practical case here presented would differ somewhat from the ideal case assumed by Fig. 5.

In said Fig. 5 the lattice reactance curve corresponds to the curve for a conventional crystal network since the capacitance

$$\frac{C_A}{2}$$

is simulated in the usual crystal network by a fixed capacitance representing the condenser effect of the crystal electrodes. The series reactance curve represents the effect of the capacitance of the series arm, represented as

$$\frac{C_0}{2}$$

in Fig. 4. As shown by the attenuation curve there is zero attenuation for the frequency interval corresponding to the positive reactance of the lattice network or, which would be a more correct way of putting it, during the interval when the reactances of the lattice network and series elements are of opposite sign. This frequency interval corresponds, therefore, to the transmission band of the network. As shown by the broken curve, the impedance over this pass band, that is, from frequency f_1 to frequency f_2, is a resistance. This would be the characteristic impedance of an ideal filter network employing the present considered network as a section. The attenuation curve shows also a linear attenuation drop beginning at the frequency corresponding to the crossing point of the two reactance curves. There is a vertical drop in the curve representing phase at this point, that is, a reversal of phase as shown in the lower curve. From that point up to the lower pass frequency the phase is constant and through the band the phase changes gradually, as shown, from the point corresponding to phase reversal to the point at the upper pass frequency corresponding to zero phase shift. In order that the amplifier or repeater tube 1 may function as an element of an oscillator, that is, in order that the circuit of Fig. 1 may function as a self-contained oscillator, it is necessary only to supply sufficient energy from the plate or anode circuit to the control electrode or grid circuit, with phase reversal, such that the gain of the tube is equal to or greater than the loss through the feedback path comprising the network. The characteristic frequency would have to lie in the pass band of the network and would, in a practical case, lie substantially at the lower cut-off frequency since at this frequency the phase is substantially completely reversed. Since the resonance of the lattice arm is controlled by the capacitance C_A, this is an effective means for producing small variations in the characteristic oscillator frequency.

The introduction of two series capacitors in the high impedance leads of the crystal would produce a similar change that C_A does but due to the very small capacitance encountered at low frequencies, ground capacitance could not be made consistently small and hence the range of adjustment with the two small series capacitors would be considerably less than with the capacitor C_A. A wide range of adjustment is necessary since these crystals are mounted in vacuum containers and are not easily removed for grinding purposes.

The invention is adaptable with slight changes of electrical environment to use with longitudinally vibrating crystals. For instance, for longitudinally vibrating crystals, adjacent plates on the same side of the crystal would have to be connected to grid and plate respectively. This would have the same equivalent circuit as shown in Fig. 4 but at higher frequencies, such as those used for longitudinally vibrating crystals, the impedance would be lower and hence would probably require transformers to match the tube. The crystal would operate at the resonance fre-

quency as before and C_A would have the same effect as in the flexure case.

It is to be understood that the invention is not to be limited to the particular embodiments described above, but only by the scope of the appended claims.

What is claimed is:

1. A crystal-controlled oscillator comprising an electron discharge device, input and output electrodes therefor including a cathode element in common thereto, a piezoelectric crystal, two pairs of oppositely disposed electrodes on the principal faces of said crystal, means connecting said pairs of electrodes to said input and output electrodes respectively through a partially common path connected to said cathode element, the ordering of said connections and the disposition of the electrodes on said crystal being such that there is reverse poling of electrostatic stress with respect to said common path so as to promote the production of flexural vibrations, and a capacitance means substantially providing all of the impedance in said common path.

2. A crystal-controlled oscillator comprising an electron discharge device, input and output electrodes therefor including a cathode in common thereto, a piezoelectric crystal, two pairs of oppositely disposed electrodes on a certain pair of opposed faces of said crystal, circuit means connecting one pair of said crystal electrodes to said input electrodes, circuit means for connecting the other pair of said crystal electrodes to said output electrodes, said circuit means which interconnect the respective pairs of crystal electrodes to the respective pairs of electron discharge device electrodes having a common path connected to said cathode, and a capacitance means providing substantially all the impedance in said common path.

3. A crystal-controlled oscillator comprising an electron discharge device, input and output electrodes therefor including a cathode in common thereto, two pairs of oppositely disposed electrodes on certain opposed faces of said crystal, circuit means connecting one of said pairs of crystal electrodes to said input electrodes, circuit means connecting said other pair of crystal electrodes to said output electrodes, said connections between the crystal electrodes and said pairs of input and output electrodes including at least a partially common path connected to said cathode and the path from said common portion through the crystal proceeding in relatively opposite directions therethrough with respect to the two pairs of crystal electrodes, and a variable capacitance means providing substantially all the impedance in said common path.

4. A crystal-controlled oscillator comprising an electron discharge device, input and output electrodes therefor, including a cathode in common thereto, a piezoelectric crystal, two pairs of oppositely disposed electrodes on the major faces of said crystal, said electrodes on each said face being on opposite sides of the medial length axis and extending in the direction of length over a substantial portion thereof, means connecting said pairs of crystal electrodes to said input and output electrodes respectively through a partially common path connected to said cathode, the interelectrode paths through the crystal being in opposite directions with respect to said common path whereby flexural vibrations in said crystal tends to be promoted, and a capacitance means providing substantially all the impedance in said common path for adjusting the vibration frequency of said crystal and therefore the characteristic frequency of the oscillator.

5. An electrical network wholly comprising a piezoelectric crystal, a pair of input terminals and a pair of output terminals therefor, two pairs of oppositely disposed electrodes on the major faces thereof, means connecting one said pair of crystal electrodes to said input terminals, means for connecting said other pair of crystal electrodes to said output terminals, said connecting circuits having a common portion and the crystal electrodes being oppositely connected to said pairs of terminals with respect to said common portion, and a capacitance means providing substantially all the impedance in said common portion.

6. An electrical network wholly comprising a pair of input terminals and a pair of output terminals, a piezoelectric crystal, two pairs of oppositely disposed electrodes on the major faces thereof, and extending over a substantial portion of the length thereof and disposed on opposite sides of the medial length axis thereof, means connecting one said pair of crystal electrodes to said input terminals, means for connecting said other pair of crystal electrodes to said output terminals and through a path at least partially in common to the first-mentioned connecting circuit, the connections to the respective pairs of crystal electrodes being reversed with respect to said common portion, whereby flexural vibrations tend to be induced, and a capacitance means providing substantially all the impedance in said common path.

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