

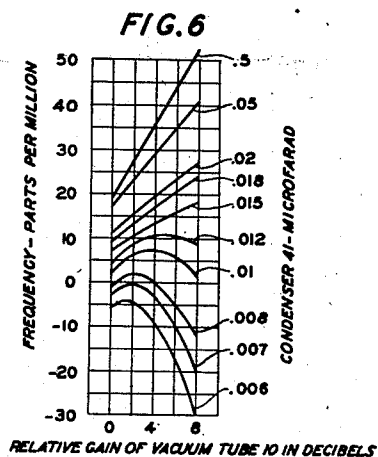
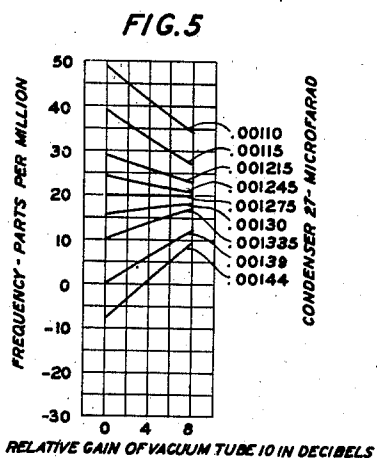
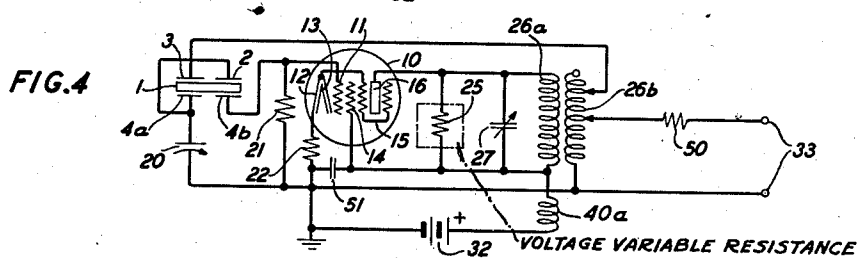
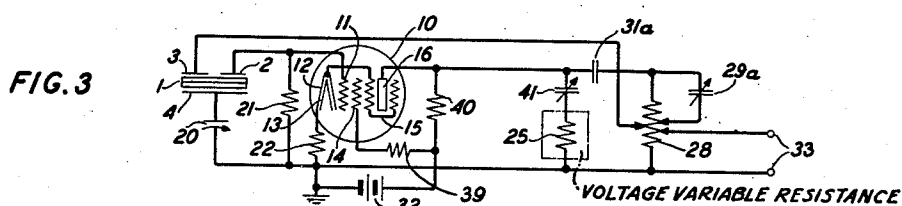
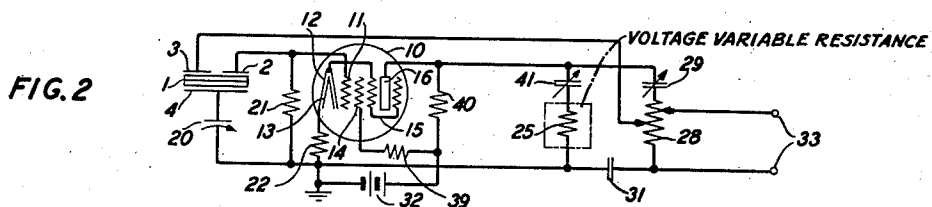
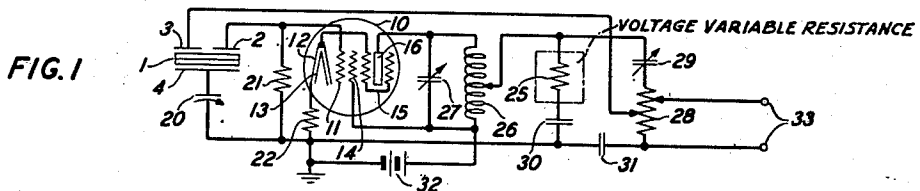
Sept. 18, 1945.

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2,385,260

CRYSTAL CONTROLLED OSCILLATOR

Filed April 30, 1943



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2,385,260

CRYSTAL CONTROLLED OSCILLATOR

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Application April 30, 1943, Serial No. 485,105

20 Claims. (Cl. 250—36)

This invention relates to oscillation generators and particularly to low frequency crystal controlled oscillation generators useful in carrier telephone systems, radio systems and transmission or receiver systems generally. Several crystal controlled oscillator circuits are particularly described for use with vibratory piezoelectric crystals which may have a low frequency of the order of 1 to 10 kilocycles per second, more or less, for example, and which may be of sufficient frequency stability to be used if desired to replace low frequency tuning fork controlled oscillators.

One of the objects of this invention is to provide a crystal controlled oscillator of high frequency stability.

Another object of this invention is to provide compensation for the natural increase in the frequency of a vibratory piezoelectric crystal body that occurs with an increase in the amplitude of motion thereof as caused by an increase in the circuit voltage applied thereto.

Another object of this invention is to provide a suitable or positive phase shift in a crystal controlled oscillatory circuit whereby the piezoelectric crystal may operate on the most desirable part of its series resonant characteristic.

In vibratory piezoelectric crystals and especially in the low frequency flexure mode types of piezoelectric crystals, the desired natural frequency of vibration of the crystal body may change as a result of a change in the amplitude of its vibration as caused by a change in the operating voltage that may be applied thereto from the oscillatory circuit in which it may be connected. Accordingly, in order to obtain a constant frequency from a piezoelectric crystal oscillation generator, it is desirable to balance out or compensate any changes in the frequency of the crystal that may be caused by changes of voltage that may be applied to the crystal.

In oscillation generator circuits, variations in the plate supply voltage from the battery, the rectifier or other plate supply source, and also variations in the gain of the oscillator vacuum tube itself may produce corresponding variations in the generated oscillating currents which when they transverse a piezoelectric crystal body that may be used to control the frequency of the oscillations generated, may cause the crystal body itself to change its frequency slightly in accordance with the changes in the amplitude of the oscillatory currents traversing it and thereby affect the frequency stability of the crystal controlled oscillator system.

be provided for compensating or balancing out the effect of the oscillatory circuit amplitude changes upon the natural frequency of the piezoelectric crystal with the result that the crystal body may maintain a high order of frequency stability for the output circuit oscillations generated. The means for balancing out the effect of such amplitude changes upon the natural frequency of the crystal body may, in accordance with one of the features of this invention, comprise the combination of a varistor or a thermistor or an equivalent voltage variable resistance with either a parallel connected inductance winding or a series connected condenser, the combination functioning to provide compensation for the natural increase in the frequency of the crystal body with an increase in the amplitude of vibration of the piezoelectric crystal body as caused by an increase in the circuit voltage applied thereto.

Also, in accordance with this invention, phase shifting means comprising a resistance potentiometer and a condenser connected in circuit relation therewith, may be provided in the oscillator output circuit to provide part of the residual phase shift in the feedback circuit, and thereby replace the usual inductance type tank circuit. The phase shifting means may, in accordance with a feature of this invention, comprise the combination of either a series connected condenser or a parallel connected condenser with a resistance potentiometer which functions to produce a suitable positive phase shift in the crystal oscillatory circuit in order to obtain improved operation thereof.

For a clearer understanding of the nature of this invention and the additional features and objects thereof, reference is made to the following description taken in connection with the accompanying drawing, in which like reference characters represent like or similar parts, and in which:

Fig. 1 is a circuit diagram illustrating a crystal controlled oscillation generator in accordance with this invention;

Fig. 2 is a circuit diagram illustrating another type of oscillation generator in accordance with this invention;

Fig. 3 is a circuit diagram illustrating a modification of the phase shifting potentiometer resistance and condenser arrangement of Figs. 1 and 2;

Fig. 4 is a circuit diagram illustrating a modification of the circuit shown in Fig. 1; and

Figs. 5 and 6 are graphs illustrating the per-

In accordance with this invention, means may

formance of particular oscillation generators constructed in accordance with Figs. 1 and 2, respectively.

Referring to the drawing, Fig. 1 is a circuit diagram illustrating a shunt inductance compensated oscillation generator controlled by a piezoelectric crystal 1. The piezoelectric crystal body 1 may be provided with field producing electrodes such as electrodes 2, 3 and 4 or other suitable electrodes that may be required to drive the crystal body 1 in the desired mode of motion and also to provide suitable circuit connections therefor. A suitable electron or space discharge tube 10 may be provided which may be, for example, an amplifier tube 10 of the pentode type having a control grid 11 connected with the crystal electrode 2, a cathode 12, a cathode heater 13, a screen grid 14, a suppressor grid 15 connected with the cathode 12, and a plate or anode 16. A crystal tuning condenser 20 may be connected in series circuit relation with the piezoelectric crystal 1 between the crystal electrode 4 and the cathode 12. A grid leak resistance 21 and a cathode resistor 22 may be provided and connected as illustrated in Fig. 1. A compensating means for balancing out the effect of crystal frequency changes is provided and may consist of a voltage variable resistance comprising a varistor 25 such as a "Thyrite" varistor, and a reactance device comprising a phase compensating retard or inductance coil 26 connected in shunt circuit relation with the varistor 25, and also, if desired, an amplitude frequency compensating trimmer condenser 27 connected in shunt relation with the inductance coil 26. A resistance potentiometer 28 and a series connected phase correcting condenser 29 may be utilized to provide a proper phase shift in the feedback circuit. The condensers 30 and 31 are by-pass condensers. A battery 32 or other suitable source may be utilized for supplying the plate 16 of the vacuum tube 10 with a suitable plate voltage through the inductance coil 26. The supply source 32 may be any suitable supply source of direct current of suitable voltage for the plate 16 and the grid 14 of the vacuum tube 10. The cathode heater 13 may be supplied with voltage from any suitable source, such as for example, a 60-cycle source of suitable voltage. Grid bias may be provided by the unbypassed cathode resistor 22 which also provides some negative feedback to stabilize the gain of the amplifier tube 10.

The adjustable capacity tuning condenser 20 connected in series circuit relation with the piezoelectric crystal body 1 may be utilized for adjusting the circuit frequency over a small range such as, for example, about one cycle per second or more. The relation between the circuit frequency and the tuning capacity of the condenser 20 may be made to be substantially a straight line relation for small departures from the series resonance frequency of the piezoelectric crystal body 1.

The piezoelectric crystal body 1 may be of any type that is suitable for controlling the frequency of the circuit with which it is connected. Preferably, the piezoelectric crystal body 1 is one the frequency of which is made substantially independent of temperature by means of temperature control or otherwise. For a low frequency of the order of 1 to 10 kilocycles per second, more or less, a flexure mode type of piezoelectric crystal 1 may be used.

As particularly illustrated in Fig. 1, and also in Figs. 2 and 3, the low frequency flexure mode type crystal 1 may be a duplex type crystal body

1 consisting of two thin flat quartz plates bonded or soldered together in major face to major face relation and provided with electrodes 2, 3 and 4 adapted to vibrate the crystal 1 in a fundamental flexure mode of motion bending in the thickness direction at a desired frequency within a range of frequencies which are practical down to a few hundred cycles per second. Examples of suitable low frequency, low temperature coefficient of frequency +5 degree X-cut duplex type quartz crystals are known in the art. Such crystals may have a parabolic frequency temperature characteristic and a very low temperature coefficient of frequency at ordinary temperatures and when utilized in the circuit described herein will give good frequency stability which may equal or better that obtained from low frequency tuning fork oscillators heretofore available. The temperature frequency curve of such a duplex type thickness bending flexure mode +5 degree X-cut quartz crystal body 1 is a parabola, and the frequency thereof may decrease only about 20 parts per million for a 40° F. change on either side of the maximum frequency point which may be controlled to a selected value within the ordinary temperature ranges such as between 60° F. and 100° F., for example. If desired, the piezoelectric crystal body 1 may be enclosed in a suitable heat insulated container in order to prevent sudden changes in the outside or room temperature from suddenly affecting the performance of the crystal 1.

Piezoelectric crystals and particularly piezoelectric crystals 1 of the low frequency flexure mode type which inherently have a relatively large magnitude of vibratory motion may considerably increase their natural resonant frequency with an increase in their amplitude of motion. If no correction is provided, this increase in the natural frequency of the piezoelectric crystal body 1 with increase in the amplitude of its vibration, called the amplitude frequency effect of the crystal, may amount to some 20 cycles per million or so if the amplitude of the voltage applied thereto is changed as a result of the change in gain of the vacuum tube 10 due to aging and differences in manufacture. To compensate for such undesired changes in the natural frequency of the crystal body 1, the varistor 25 and the shunt connected inductance winding 26 may be disposed in the output circuit of the vacuum tube 10 in order to provide means responsive to voltage changes in the output circuit for balancing out the frequency change in the crystal body 1, whereby the output circuit frequency of the system may remain substantially constant.

The varistor 25 may be a voltage variable resistance of the silicon carbide "Thyrite" type as disclosed, for example, in McEachron Patent 1,822,742, dated September 8, 1931. Alternatively, the voltage variable resistance 25 may be a negative temperature coefficient thermistor or other suitable voltage variable resistance device the resistance of which decreases with increased voltage applied thereto and which functions as a voltage or current limiter for controlling the magnitude of voltage and current of the circuit in which it is connected. As particularly disclosed herein, the voltage variable resistance device 25 is a varistor of the "Thyrite" type referred to which responds very quickly to voltage changes as compared to the usual thermistor for example. The "Thyrite" varistor 25 which is connected across the output circuit of the oscillation generator tube 10 functions in part as a

voltage limiter in order to limit the generated output voltage that is placed across its terminals to a maximum value such as for example 6 to 10 volts or other value to suit the circuit. The varistor 25 may receive its voltage from the plate 16 of the vacuum tube 10 through the inductance coil 26 and from the cathode 12 through the cathode resistor 22 and the by-pass condenser 30, and functions to limit and control the output circuit voltage that is applied to the resistance potentiometer 28 which supplies voltage to the output terminals 33 of the oscillator system and which also supplies a stepped-down feedback voltage of suitable value to the electrode 3 of the piezoelectric crystal body 1. By limiting and controlling the amplitude of the output circuit voltage, the varistor 25 controls the amplitude of the voltage applied to the piezoelectric crystal body 1 and thereby prevents to some extent changes in the frequency of the piezoelectric crystal body 1 due to changes in the amplitude of the voltage applied thereto. As pointed out hereinbefore, it will be understood that the piezoelectric crystal body 1 controls the frequency of the oscillator and will change its resonant frequency slightly with a change of the amplitude of its vibration as caused by a change in amplitude of the circuit voltage applied thereto.

The inductance winding 26 in combination with the varistor 25 provides a change in phase with a change in amplitude of the output circuit voltage that reduces the frequency of the output circuit as the voltage thereof increases, thereby balancing out the increase in the natural frequency of the piezoelectric crystal 1 caused by the increase in the voltage of the output circuit. The inductance value of the coil 26 may be so chosen that the two effects nearly cancel or balance out, as illustrated in Fig. 5 where typical curves show the relation of the overall output frequency to the gain of the vacuum tube 10 in an oscillator circuit of the type shown in Fig. 1.

To obtain the proper value of inductance for the inductance coil 26, it is often more convenient in practice to choose a standard retard coil 26 rather than a special one 26 and to adjust its effective inductance at the oscillator frequency by means of the amplitude frequency compensating trimmer condenser 27 which is connected in shunt circuit relation therewith, as illustrated in Fig. 1. The condenser 27 connected in shunt circuit relation with the inductance coil 26 and coacting with the varistor 25 then function together to change the phase and reduce the circuit frequency as the circuit voltage goes up or increases, and to increase the circuit frequency as the amplitude decreases thereby balancing out the change in the natural frequency of the piezoelectric crystal body 1 due to a change in the gain of the vacuum tube 10. The inductance coil 26 may be provided with adjustable taps, if desired, which may be used to obtain additional gain, or the circuit may be used with a single winding coil 26, if desired. It will be noted that the tuned retard or inductance coil 26 in combination with the parallel connected condenser 27 of Fig. 1 furnishes an inductive reactance of the proper amount so that when combined with the "Thyrite" voltage limiter 25, there is produced a phase shift with voltage change therein that balances out the increase in the natural frequency of the piezoelectric crystal body 1 produced by an increase of its amplitude of motion. Accord-

ingly, the oscillator circuit illustrated in Fig. 1 may combine parallel connected inductance 26 and capacitance 27 devices with a varistor or a thermistor 25 in such a manner as to balance out any amplitude effect on the frequency of the crystal 1 due to battery voltage supply variations or to oscillation tube variations for example.

The oscillator circuit as illustrated in Fig. 1 may be provided with a resistor-condenser type of phase shifting means 28, 29 in order to provide part of the residual phase shift in the feedback circuit which the usual inductance type of tank circuit normally provides. The phasing condenser 29 connected in series circuit relation with the resistance 28 may be made of a value of capacitance to provide such additional phase shift in the feedback circuit to the piezoelectric crystal 1 that the piezoelectric crystal 1 may operate at its series resonance frequency and on the optimum part of its characteristic. The output circuit potentiometer consisting of the condenser 29 and the resistance 28 provides the residual phase shift referred to which causes the piezoelectric crystal body 1 to operate at its proper series resonant frequency. The output circuit potentiometer 28 also permits the "Thyrite" varistor 25 to be made for and operated at a convenient and suitable voltage therefor, such as for example a voltage of the order of 7 to 10 volts, while the piezoelectric crystal body 1 simultaneously operates at a much lower voltage such as for example a voltage of less than one volt. That is, the output circuit resistance potentiometer 28 may be utilized to step down the voltage across the varistor 25 to a suitable small value such as for example one volt or less, and by means of the connection to the crystal electrode 3 to apply that small stepped down voltage to the piezoelectric crystal body 1. A small voltage on the piezoelectric crystal body 1 is usually desirable from a standpoint of optimum stability. The output circuit resistance potentiometer 28, by means of a tap as illustrated, may conveniently provide a variable output voltage to the output terminals 33, the voltage being variable in approximately 2 decibel steps for example.

As an illustrative example, typical values for the component parts of the oscillator circuit of Fig. 1 may be roughly as follows for a frequency of 4 kilocycles per second, it being understood that these values may be varied somewhat to best suit the application and to accomplish the objects of the invention. The condenser 20 may be about .001 to .01 microfarad as required to obtain the proper frequency, the resistance 21 about 100,000 ohms, the resistance 22 about 600 ohms, the source 32 about 135 volts, the condenser 30 about 1.0 microfarad, and the condenser 31 about 1.0 microfarad. The "Thyrite" varistor 25 may be about 10,000 ohms voltage variable, the retard coil 26 about 200 ohms and 1.0 henry, the condenser 27 about .0013 microfarad, the resistance 28 about 100,000 ohms, and the condenser 29 about .0009 microfarad, the parts being adjusted to related values that they may operate to accomplish the balancing and the phase shifting functions assigned to them as hereinbefore described.

The oscillator output system may be connected at its output terminals 33 to any suitable amplifier and also to a harmonic generator, if desired. The amplifier may serve to intensify the signal produced by the oscillator and, if desired, to provide means for cutting off the output of the gen-

erator when required. The harmonic producer may generate various harmonics of the oscillator output frequency which may be used as carriers for various channels of multichannel carrier telephone systems for example.

Fig. 2 is a circuit diagram of a modification of the oscillator circuit of Fig. 1. As illustrated in Fig. 2, a resistor 40 which may have a resistance of about .1 megohm or other suitable value, may be utilized and substituted in place of the retard coil 26 of Fig. 1 to furnish the plate supply voltage from the source 32 to the plate 16 of the vacuum type pentode tube 10. Also, if desired, a resistance 39 of about .24 megohm or other suitable value may be utilized in the supply circuit to the screen grid 14 of the vacuum tube 10. In place of the inductance coil 26 and the shunt connected condenser 27 of Fig. 1, a condenser 41 having a capacitance of about .01 microfarad or other suitable value may be connected in series circuit relation with the varistor 25 as illustrated in Fig. 2 and utilized to provide the amplitude frequency correction which is provided in the circuit of Fig. 1 by the inductance coil 26 and the varistor 25. The correction provided by the series condenser 41 and varistor 25 arrangement of Fig. 2 is not as perfect as that which can be provided by the varistor 25 and shunt inductance coil 26 arrangement of Fig. 1, as is illustrated by the curves of Fig. 6 in comparison with those of Fig. 5, since in the Fig. 2 oscillator arrangement, the residual error may amount to more, such as some 2 to 5 parts per million depending upon the gain instability of the vacuum tube 10 that may be utilized in the circuit. The correction provided by the varistor 25 and the series compensating condenser 41 of Fig. 2 is, however, good enough for many or most applications and is of special interest where weight or cost is a factor and the avoidance of coils is of interest.

The voltage variable resistance 25 or the thermal variable resistance 25 when used with the series connected condenser 41 of Fig. 2, like the parallel connected varistor 25 and inductance 26 arrangement of Fig. 1, responds to amplitude changes in the output circuit of the vacuum tube 10 to cause a voltage phase change that is equal and opposite in magnitude and sign to the voltage phase change caused in the piezoelectric crystal body 1 by said amplitude change, thereby keeping the system output circuit frequency at the terminals 33 of substantially constant value irrespective of the voltage changes in the output circuit of the vacuum tube 10. Since the amplitude of the output voltage is limited by the varistor 25, any effect of the source 32 voltage upon the output circuit frequency is due mainly to the resulting change in the gain of the vacuum tube 10, and this effect is minimized by the balancing out of the amplitude effect by means of the varistor 25 and the shunt inductance coil 26 of Fig. 1, or by the varistor 25 and the series condenser 41 of Fig. 2. The oscillator of Fig. 2 which combines the series condenser 41 with the varistor 25 to balance out the amplitude effect due to battery or tube variations, also has a resistor-condenser type of phase shifting means 28, 29 of the same type and for the same purposes as has been described in connection with Fig. 1. The oscillator circuit of Fig. 2 gives slightly less frequency stability than that of Fig. 1 as is illustrated by the curves of Fig. 6 in comparison with those of Fig. 5.

Fig. 3 is a circuit diagram of an oscillator which

is similar to that illustrated in Fig. 2. In Fig. 3 as in Fig. 2, the combination of the varsitor 25 connected in series circuit relation with the condenser 41 is made to have values that give an amplitude and phase characteristic which is equal and opposite to that of the piezoelectric crystal 1 as described hereinbefore. The output circuit frequency at the terminals 33 of the crystal controlled oscillator of Fig. 3 is then substantially independent of the amplitude of oscillation and so is independent of the gain of the vacuum tube 10 over a wide range. In Fig. 3, a phasing condenser 29a having a capacitance of about .0004 microfarad or other suitable value is combined with the resistance potentiometer 28 in shunt relation instead of in series relation as in Fig. 2 so as to provide a suitable positive phase shift in the feedback circuit for proper operation of the piezoelectric crystal body 1. For this purpose, it will be understood that either the Fig. 3 shunt condenser 29a of suitable value, or the Fig. 2 series condenser 29 of suitable value may be utilized with the resistance 28 to accomplish the same result. The resistance potentiometer 28 steps down the voltage supplied from the varistor 25 to the piezoelectric crystal 1 so that both may operate at suitable voltages, and the condenser 29a of Fig. 3 shunted across the high voltage arm of the resistance 28, or the condenser 29 of Figs. 1 and 2 connected in series circuit relation with the resistance 28 produces a phase shift of such a value that the piezoelectric crystal body 1 operates on a desirable part of its characteristic. The value of the phase shift may be of the order of 40 degrees for example or other value to suit the operating characteristics of the particular piezoelectric crystal body 1. The phasing condenser 29 or 29a may be placed in shunt with the resistance potentiometer 28 as illustrated in Fig. 3, or alternatively in series therewith as illustrated in Figs. 1 and 2 in order to provide a suitable phase shift in the feedback circuit, in addition to that provided by the crystal body 1 itself.

In Fig. 3 as in Fig. 2, the varsitor or thermistor 25 limits and controls the amplitude of the voltage, and the condenser 41 connected in series circuit relation with the varsitor or thermistor 25 may have values so chosen that a change in gain of the vacuum tube 10, which may cause the change in amplitude, produces a phase shift that is equal and opposite to that produced in the piezoelectric crystal body 1 by the same change in amplitude. The balancing effect may extend over a range of several decibels and is a result of the fact that the amplitude change will change the series resistance but not the series reactance of the condenser 41 and the varsitor 25 combination. As a particular example, the condenser 41 of Figs. 2 and 3 may have a capacitance value of the order of about .01 microfarad for an amplitude frequency balance for 4 kilocycles per second, and a smaller value for a lower frequency. If desired, the blocking condenser 31a and the phase adjusting condenser 29a of Fig. 3 may be combined into a single condenser of equivalent value at the fundamental frequency. Also the resistance 40 may alternatively be a large retard coil.

Fig. 4 is a circuit diagram of an oscillator similar to that of Fig. 1 but provided with a step down transformer having secondary winding 26b which supplies feedback voltage of suitable magnitude and phase for the piezoelectric crystal body 1 and a primary winding 26a which is connected in parallel circuit relation with the varis-

tor or thermistor 25 and a condenser 27. The tuned circuit comprising the inductance winding 26a and the condenser 27 is tuned off frequency so as to give with the varistor 25 an amplitude and phase characteristic that is equal and opposite to that of the piezoelectric crystal body 1 so that the net phase shift around the feedback loop is near zero over a wide range of changes in amplitudes. The frequency of the oscillator at the output terminals 33 may then be independent of the amplitude of oscillations generated and accordingly independent of the gain of the vacuum tube 10 over a wide range. This results from the fact that the phase shift through the detuned circuit 26a and 27 paralleled by the voltage variable resistance 25 is a function of the value of the resistance 25 at all frequencies except the tuned frequency. In the oscillator circuit of Fig. 4, the output transformer 26a, 26b is tuned by the condenser 27, which in practice may be adjusted to a value such that the frequency is not changed when the gain of the tube 10 is changed, as by changing to other tubes of different gain or by changing the amount of negative feedback, if used. The frequency may then be adjusted to its final value by the condenser 20 associated with the piezoelectric crystal body 1. The frequency may be made stable to a few parts in ten million with tube gain changes of several decibels.

As illustrated in Fig. 4, a resistance 50, if desired, may be provided in the output circuit terminal connection 33, and also a retard coil 40a may be placed in circuit with the plate supply source 32. As a simple test procedure, a by-pass condenser (not shown) may be placed across the cathode resistance 22, and then the condenser 27 may be adjusted to a value such that the association of the resistance 22 with such by-pass condenser changes the frequency a minimum amount, not to exceed about one part per million, for example.

As particularly illustrated in Fig. 4, the low frequency piezoelectric crystal body 1 may consist of a single quartz plate with each of its major face coatings or platings split lengthwise to form the four electrodes 2, 3, 4a and 4b, and adapted to produce low frequency flexure mode vibrations bending in the width dimension, as disclosed in W. P. Mason Patent 2,250,317 dated October 14, 1941 and R. A. Sykes Patent 2,300,075 dated October 27, 1942. If such a width bending crystal body 1 of Fig. 4 becomes too long and too thin to be used at the lower frequencies, such as for example a frequency below 10 kilocycles per second, a duplex type thickness bending crystal body 1 of the type illustrated in Figs. 1, 2 and 3 may be utilized down to a few hundred cycles per second. While particular piezoelectric crystals 1 have been shown in connection with the circuits of Figs. 1 to 4, it will be understood that any suitable piezoelectric crystal body 1 may be utilized.

Fig. 5 is a graph illustrating the effect of changes in the capacitance of the compensating trimmer condenser 27 on the shunt inductance coil 26 and the corresponding effect on the output frequency of a particular oscillator of the Fig. 1 type, for various values in the relative gain of the vacuum tube 10 as expressed in decibels (db.). As illustrated by the horizontal curve in Fig. 5 labeled .001275 microfarad, it will be noted that the shunt inductance compensated crystal controlled oscillator circuit of Fig. 1 may be adjusted to have a high frequency stability over a wide gain of the vacuum tube 10. Similar results may be obtained with the oscillator circuit of the type

as illustrated in Fig. 4 which also utilizes an inductance connected in shunt with the varistor 25 to balance out changes in the natural frequency of the piezoelectric crystal body 1.

Fig. 6 is a graph similar to Fig. 5 but illustrating the effect of changes in the capacitance of the series connected compensating condenser 41 and the corresponding effect on the output frequency of a particular oscillator of the Fig. 2 type, for various values in the relative gain of the vacuum tube 10. As illustrated by the curve in Fig. 6, labeled .01 microfarad for example, representing the capacitance of the condenser 41, the oscillator circuit of Fig. 2 will have a frequency stability slightly less than that obtained from the circuit of Fig. 1. Similar results may be obtained from the circuit illustrated in Fig. 3 which also utilizes the series connected condenser 41 and varistor 25 to balance out changes in the frequency of the piezoelectric crystal body 1.

The phase angle relation θ between the current and the voltage e for the shunt inductance coil 26 and the varistor 25 combination as illustrated in Fig. 1 for example is given by the relation:

$$\tan \theta = \frac{R_0}{e^{\eta} X} \quad (1)$$

where e is the voltage across the varistor 25 and the shunt connected part of the inductance coil 26;

η as a value typically over 2.5;

X is the reactance of the inductance coil 26 connected in parallel circuit relation with the varistor 25; and

R_0 is a value in the relation

$$R = \frac{R_0}{e^{\eta}}$$

where R is the resistance of the varistor 25.

As illustrated by Equation 1, the phase angle θ between the voltage e and the current of the varistor 25 and the inductance coil 26 of Fig. 1 decreases or changes in a negative direction with an increase in the voltage e , and the values of the varistor 25 and the inductance 26 may be adjusted to almost exactly compensate the piezoelectric crystal body 1 over a voltage range of some 3 or 4 or more to 1.

The phase angle relation θ between the current and the voltage e for the series condenser 41 and the varistor 25 combination of Fig. 2 for example is given by the relation:

$$\tan \theta = -\frac{e^{\eta} X}{R_0} \quad (2)$$

where e is the voltage across the outer terminals of the varistor 25 and the condenser 41 connected in series therewith;

η is a value typically over 2.5;

X is the reactance of the condenser 41; and

R_0 is a value in the relation

$$R = \frac{R_0}{e^{\eta}}$$

where R is the resistance of the varistor 25.

As illustrated by Equation 2, the phase angle θ between the voltage e and the current of the varistor 25 and the condenser 41 of Fig. 2 also decreases or changes in a negative direction with an increase in voltage e , and the values of the varistor 25 and the condenser 41 may be adjusted to compensate the crystal 1 over a range that is good enough for many or most applications.

In order to neutralize the negative phase shift produced by the varistor 25 and the shunt in-

ductance 26 and stray capacitances in the circuit of Fig. 1 as shown by Equation 1, or that produced by the varistor 25 and the series condenser 41 and stray capacitances in the circuit of Fig. 2, as shown by Equation 2, a positive phase shift may be provided by means of the condenser 29 of Figs. 1 and 2 connected in series circuit relation with the potentiometer resistance 28 thereof. The positive phase shift angle θ is given by the relation:

$$\tan \theta = -\frac{-X}{R} = \frac{X}{R} \quad (3)$$

where:

X is the reactance of the condenser 29; and
R is the resistance of the resistance 28.

In case an inductance type potentiometer is used, as in the circuit of Fig. 4, in place of the resistance potentiometer 28 of Figs. 1, 2 and 3, a positive phase shift condenser 29 may not be needed for that purpose since the inductance itself may produce the required positive feedback phase shift to cause the circuit to oscillate nicely.

Although this invention has been described and illustrated in relation to specific arrangements, it is to be understood that it is capable of application in other organizations and circuits and is therefore not to be limited to the particular embodiments disclosed.

What is claimed is:

1. A crystal controlled oscillation generator comprising an electron discharge device having input, output and feedback circuits, a flexure mode piezoelectric crystal body having electrodes connected with said input circuit and said feedback circuit, a condenser disposed in said input circuit and connected in series circuit relation with said piezoelectric crystal body, means including a potentiometer in said output circuit for providing a step down voltage through said feedback circuit to said piezoelectric crystal body, and means including a voltage variable resistance and a cooperating reactance disposed in said output circuit and responsive to voltage change in said output circuit for balancing out the change in the natural frequency of said crystal body caused by said output circuit voltage change whereby the output frequency of said generator is rendered substantially constant and independent of said frequency change in said crystal body.

2. A crystal controlled oscillation generator comprising an electron discharge device having input, output and feedback circuits, a flexure mode piezoelectric crystal body having electrodes connected with said input circuit and said feedback circuit, a condenser disposed in said input circuit and connected in series circuit relation with said crystal body, means including a potentiometer in said output circuit for providing a step down voltage through said feedback circuit to said crystal body, and means including a voltage variable resistance and a cooperating reactance disposed in said output circuit and responsive to voltage change in said output circuit for balancing out the change in the frequency of said crystal body caused by said output circuit voltage change whereby the output frequency of said generator is rendered substantially constant and independent of said frequency change in said crystal body, said reactance means comprising an inductance winding, said winding being connected in shunt circuit relation with said voltage variable resistance.

3. A crystal controlled oscillation generator comprising an electron discharge device having

input, output and feedback circuits, a flexure mode piezoelectric crystal body having electrodes connected with said input circuit and said feedback circuit, a condenser disposed in said input circuit and connected in series circuit relation with said crystal body, means including a potentiometer in said output circuit for providing a step down voltage through said feedback circuit to said crystal body, and means including a voltage variable resistance and a cooperating reactance disposed in said output circuit and responsive to voltage change in said output circuit for balancing out the change in frequency of said crystal body caused by said output circuit voltage change whereby the output frequency of said generator is rendered substantially constant and independent of said crystal body frequency change, said reactance means comprising an inductance winding and a condenser connected in shunt circuit relation with said inductance winding, said reactance means being connected in shunt circuit relation with said voltage variable resistance.

4. A crystal controlled oscillation generator comprising an electron discharge device having input, output and feedback circuits, a flexure mode piezoelectric crystal body having electrodes connected with said input circuit and said feedback circuit, a condenser disposed in said input circuit and connected in series circuit relation with said crystal body, means including a potentiometer in said output circuit for providing a step down voltage through said feedback circuit to said crystal body, and means including a voltage variable resistance and a cooperating reactance disposed in said output circuit and responsive to voltage change in said output circuit for balancing out the change in frequency of said crystal body caused by said output circuit voltage change whereby the output frequency of said generator is rendered substantially constant and independent of said crystal body frequency change, said reactance means comprising a condenser, said last-mentioned condenser being connected in series circuit relation with said voltage variable resistance.

5. A crystal controlled oscillation generator comprising an electron discharge device having input, output and feedback circuits, a piezoelectric crystal body having electrodes connected with said input circuit and said feedback circuit, a condenser connected in series circuit relation with said crystal body, means including a potentiometer in said output circuit for providing a step down voltage through said feedback circuit to said crystal body, and means including a voltage variable resistance and a cooperating reactance disposed in said output circuit and responsive to voltage change in said output circuit for balancing out the change in frequency of said crystal body caused by said output circuit voltage change whereby the output frequency of said generator is rendered substantially constant and independent of said crystal body frequency change, said voltage variable resistance comprising silicon carbide.

6. A crystal controlled oscillation generator comprising an electron discharge device having input, output and feedback circuits, a piezoelectric crystal body having electrodes connected with said input circuit and said feedback circuit, a condenser connected in series circuit relation with said crystal, means including a potentiometer in said output circuit for providing a step down voltage through said feedback cir-

cuit to said crystal body, and means including a voltage variable resistance and a cooperating reactance disposed in said output circuit and responsive to voltage change in said output circuit for balancing out the change in frequency of said crystal body caused by said output circuit voltage change whereby the output frequency of said generator is rendered substantially constant and independent of said crystal body frequency change, said voltage variable resistance being a resistance which decreases in resistance value with increased voltage change applied thereto from said output circuit.

7. A crystal controlled oscillation generator comprising an electron discharge device having input, output and feedback circuits, a piezoelectric crystal body having electrodes connected with said input circuit and said feedback circuit, a condenser in said input circuit and connected in series circuit relation with said crystal body, means including a potentiometer in said output circuit for providing a step down voltage through said feedback circuit to said crystal body, and means including a voltage variable resistance and a cooperating reactance disposed in said output circuit and responsive to voltage change in said output circuit for balancing out the change in frequency of said crystal body caused by said output circuit voltage change whereby the output frequency of said generator is rendered substantially constant and independent of said crystal body frequency change, said potentiometer comprising a resistance and a phase shifting condenser, said phase shifting condenser being connected in series circuit relation with said potentiometer resistance and having a capacitance of a value to permit said crystal body to operate on a desired part of its series resonance characteristic.

8. A crystal controlled oscillation generator comprising an electron discharge device having input, output and feedback circuits, a piezoelectric crystal body having electrodes connected with said input circuit and said feedback circuit, a condenser in said input circuit and connected in series circuit relation with said crystal body, means including a potentiometer in said output circuit for providing a step down voltage through said feedback circuit to said crystal body, and means including a voltage variable resistance and a cooperating reactance disposed in said output circuit and responsive to voltage change in said output circuit for balancing out the change in frequency of said crystal body caused by said output circuit voltage change whereby the output frequency of said generator is rendered substantially constant and independent of said crystal body change, said potentiometer comprising a resistance and a phase shifting condenser, said phase shifting condenser being connected in parallel circuit relation with said potentiometer resistance and having a capacitance of a value to permit said crystal body to operate on a desired part of its series resonance characteristic.

9. A crystal controlled oscillation generator comprising an electron discharge device having input, output and feedback circuits, a piezoelectric crystal body having electrodes connected with said input circuit and said feedback circuit, means including a potentiometer in said output circuit for providing a step down voltage through said feedback circuit to said crystal body, and means including a voltage variable resistance and a cooperating reactance disposed in said output circuit and responsive to voltage change in said

output circuit for balancing out the change in frequency of said crystal body caused by said output circuit voltage change whereby the output frequency of said generator is rendered substantially independent of said crystal body frequency change, said potentiometer comprising a resistance and a phase shifting condenser, said condenser being connected in series circuit relation with said potentiometer resistance and having a capacitance of a value to permit said crystal body to operate on the optimum part of its series resonance characteristic, and said reactance means comprising an inductance winding and a condenser, said last-mentioned condenser being connected in shunt circuit relation with said inductance winding.

10. A crystal controlled oscillation generator comprising an electron discharge device having input, output and feedback circuits, a flexure mode piezoelectric crystal body connected in said feedback circuit, a condenser in said input circuit and connected in series circuit relation with said crystal body, means including a potentiometer in said output circuit for providing a step down voltage through said feedback circuit to said crystal body, and means including a voltage variable resistance and a cooperating reactance disposed in said output circuit and responsive to voltage change in said output circuit for balancing out the change in frequency of said crystal body caused by said output circuit voltage change whereby the output frequency of said generator is rendered substantially constant independent of said crystal body frequency change, said potentiometer comprising a resistance and a phase shifting condenser, said phase shifting condenser being connected in series circuit relation with said last-mentioned resistance and having a capacitance of a value to permit said crystal to operate on a desired part of its series resonance characteristic, said reactance means comprising an inductance winding and a condenser, said last-mentioned condenser being connected in shunt circuit relation with said inductance winding, and said voltage variable resistance being a resistance device comprising silicon carbide connected in shunt circuit relation with said reactance means.

11. A crystal controlled oscillation generator comprising an electron discharge device having input, output and feedback circuits, a flexure mode piezoelectric crystal body connected in said feedback circuit, a condenser in said input circuit and connected in series circuit relation with said crystal body, means including a potentiometer in said output circuit for providing a step down voltage through said feedback circuit to said crystal body, and means including a voltage variable resistance and a cooperating reactance disposed in said output circuit and responsive to voltage change in said output circuit for balancing out the change in frequency of said crystal body caused by said output circuit voltage change whereby the output frequency of said generator is rendered substantially constant and independent of said crystal body frequency change, said potentiometer comprising a resistance and a phase shifting condenser, said phase shifting condenser being connected in series circuit relation with said last-mentioned resistance and having a capacitance of a value to permit said crystal body to operate on a desired part of its series resonance characteristic, said reactance means comprising an inductance winding and a condenser, said last-mentioned condenser

being connected in shunt circuit relation with said inductance winding, and said voltage variable resistance being a resistance which decreases in resistance value with increased voltage change applied thereto from said output circuit.

12. A crystal controlled oscillation generator comprising an electron discharge device having input, output and feedback circuits, a piezoelectric crystal body connected in said feedback circuit, a condenser in said input circuit and connected in series circuit relation with said crystal body, means including a potentiometer in said output circuit for providing a step down voltage through said feedback circuit to said crystal body, and means including a voltage variable resistance and a cooperating reactance disposed in said output circuit and responsive to voltage change in said output circuit for balancing out the change in frequency of said crystal body caused by said output circuit voltage change whereby the output frequency of said generator is rendered substantially constant and independent of said crystal body frequency change, said potentiometer comprising a resistance and a phase shifting condenser, said phase shifting condenser being connected in series circuit relation with said last-mentioned resistance and having a capacitance of a value to permit said crystal to operate on a desired part of its series resonance characteristic, said reactance means comprising a condenser, said last-mentioned condenser being connected in series circuit relation with said voltage variable resistance.

13. A crystal controlled oscillation generator comprising an electron discharge device having input, output and feedback circuits, a piezoelectric crystal body in said feedback circuit, a condenser in said input circuit and connected in series circuit relation with said crystal body, means including a potentiometer in said output circuit for providing a step down voltage through said feedback circuit to said crystal body, and means including a voltage variable resistance and a cooperating reactance disposed in said output circuit and responsive to voltage change in said output circuit for balancing out the change in frequency of said crystal body caused by said output circuit voltage change whereby the output frequency of said generator is rendered substantially constant and independent of said crystal body frequency change, said potentiometer comprising a resistance and a phase shifting condenser, said last-mentioned condenser being connected in series circuit relation with said last-mentioned resistance and having a capacitance of a value to permit said crystal body to operate on a desired part of its series resonance characteristic, said reactance comprising a condenser, said last-mentioned condenser being connected in series circuit relation with said voltage variable resistance, said voltage variable resistance being a resistance device comprising silicon carbide.

14. A crystal controlled oscillation generator comprising an electron discharge device having input, output and feedback circuits, a piezoelectric crystal body connected with said feedback circuit, a condenser in said input circuit and connected in series circuit relation with said crystal body, means including a potentiometer in said output circuit for providing a step down voltage through said feedback circuit to said crystal body, and means including a voltage variable resistance and a cooperating reactance disposed in said output circuit and responsive to voltage change in said output circuit for balancing or compensat-

ing the change in frequency of said crystal body caused by said output circuit voltage change whereby the output frequency of said generator is rendered substantially constant and independent of said crystal body frequency change, said potentiometer comprising a resistance and a phase shifting condenser, said last-mentioned condenser being connected in series circuit relation with said last-mentioned resistance and having a capacitance of a value to permit said crystal body to operate on a desired part of its series resonance characteristic, said reactance comprising a condenser connected in series circuit relation with said voltage variable resistance, said voltage variable resistance being a resistance which decreases in resistance value with increased voltage change applied thereto from said output circuit.

15. A crystal controlled oscillation generator comprising an electron discharge device having input, output and feedback circuits, a flexure mode piezoelectric crystal body having electrodes connected with said input circuit and said feedback circuit, a condenser in said input circuit and connected in series circuit relation with said crystal body, means including a potentiometer in said output circuit for providing a step down voltage through said feedback circuit to said crystal body, and means including a voltage variable resistance and a cooperating reactance disposed in said output circuit and responsive to voltage change in said output circuit for balancing or compensating the change in frequency of said crystal body caused by said output circuit voltage change whereby the output frequency of said generator is rendered substantially constant and independent of said crystal body frequency change, said potentiometer comprising a resistance and a phase shifting condenser connected in parallel circuit relation with said last-mentioned resistance, said last-mentioned condenser having a capacitance of a value to permit said crystal body to operate on a desired part of its series resonance characteristic, said reactance comprising a condenser connected in series circuit relation with said voltage variable resistance, said voltage variable resistance being a resistance device comprising silicon carbide.

16. A crystal controlled oscillation generator comprising an electron discharge device having input, output and feedback circuits, a piezoelectric crystal body connected with said feedback circuit, means including a potentiometer in said output circuit for providing a step down voltage through said feedback circuit to said crystal body, and means including a voltage variable resistance and a cooperating reactance disposed in said output circuit and responsive to voltage change in said output circuit for balancing or compensating the change in frequency of said crystal body caused by said output circuit voltage change whereby the output frequency of said generator is rendered substantially constant and independent of said crystal body frequency change, said potentiometer comprising a resistance and a phase shifting condenser connected in parallel circuit relation with said last-mentioned resistance, said condenser having a capacitance of a value to permit said crystal body to operate on a desired part of its series resonance characteristic, said reactance comprising a condenser connected in series circuit relation with said voltage variable resistance, said voltage variable resistance being a resistance which decreases in resistance value with an increase of said volt-

age change applied thereto from said output circuit.

17. An oscillation generator comprising an electron tube having input, output and feedback circuits, a piezoelectric crystal body connected in said feedback circuit, a voltage variable resistance, and an inductance connected in parallel circuit relation with said resistance, said resistance and inductance being disposed in said output circuit and together constituting cooperating means responsive to voltage change in said output circuit for changing the magnitude and phase and hence the frequency thereof and thereby comprising means for balancing out the change in the natural frequency of said crystal body caused by said output circuit voltage change whereby the resultant output frequency of said generator is rendered substantially constant and independent of said frequency change in said crystal body.

18. An oscillator generator comprising an electron tube having input, output and feedback circuits, a piezoelectric crystal body connected in said feedback circuit, a voltage variable resistance, and a condenser connected in series circuit relation with said resistance, said resistance and condenser being disposed in said output circuit and together constituting cooperating means responsive to voltage change in said output circuit for changing the magnitude and phase and hence the frequency thereof and thereby comprising means for balancing out the change in the natural frequency of said crystal body caused by said output circuit voltage change whereby the resultant output frequency of said generator is

rendered substantially constant and independent of said frequency change in said crystal body.

19. An oscillation generator comprising an electron tube having input, output and feedback circuits, a piezoelectric crystal body connected in said feedback circuit of said tube, a voltage variable resistance, and an inductance connected in parallel circuit relation with said resistance, said resistance and inductance being disposed in said output circuit and together constituting cooperating means responsive to voltage change in said output circuit for changing the frequency thereof, said frequency change being a value substantially equal and opposite to the change in the natural frequency of said crystal body that occurs with a change in the amplitude of motion thereof as caused by said output circuit voltage change.

20. An oscillation generator comprising an electron tube having input, output and feedback circuits, a piezoelectric crystal body connected in said feedback circuit of said tube, a voltage variable resistance and a condenser connected in series circuit relation with said resistance, said resistance and condenser being disposed in said output circuit and together constituting cooperating means responsive to voltage change in said output circuit for changing the frequency thereof, said frequency change being a value substantially equal and opposite to the change in the natural frequency of said crystal body that occurs with a change in the amplitude of motion thereof as caused by said output circuit voltage change.

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