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June 29, 1948. C. W. HARRISON **2,444,349**

CRYSTAL OSCILLATOR CIRCUITS

Filed Oct. 31, 1945 2 Sheets-Sheet 1

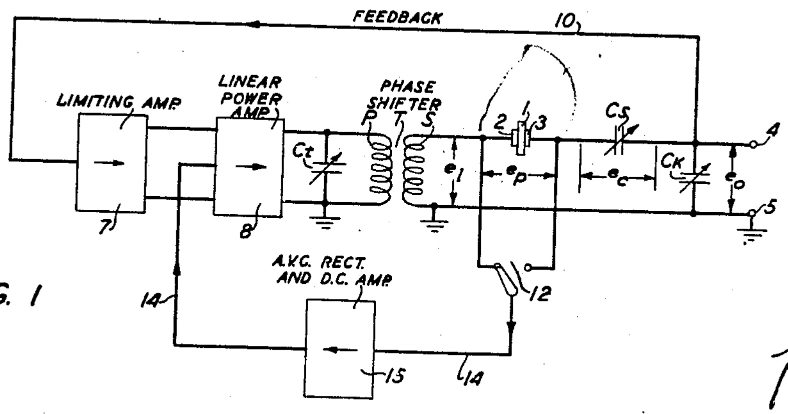

FIG. 1

piezo

feedback circuit 10

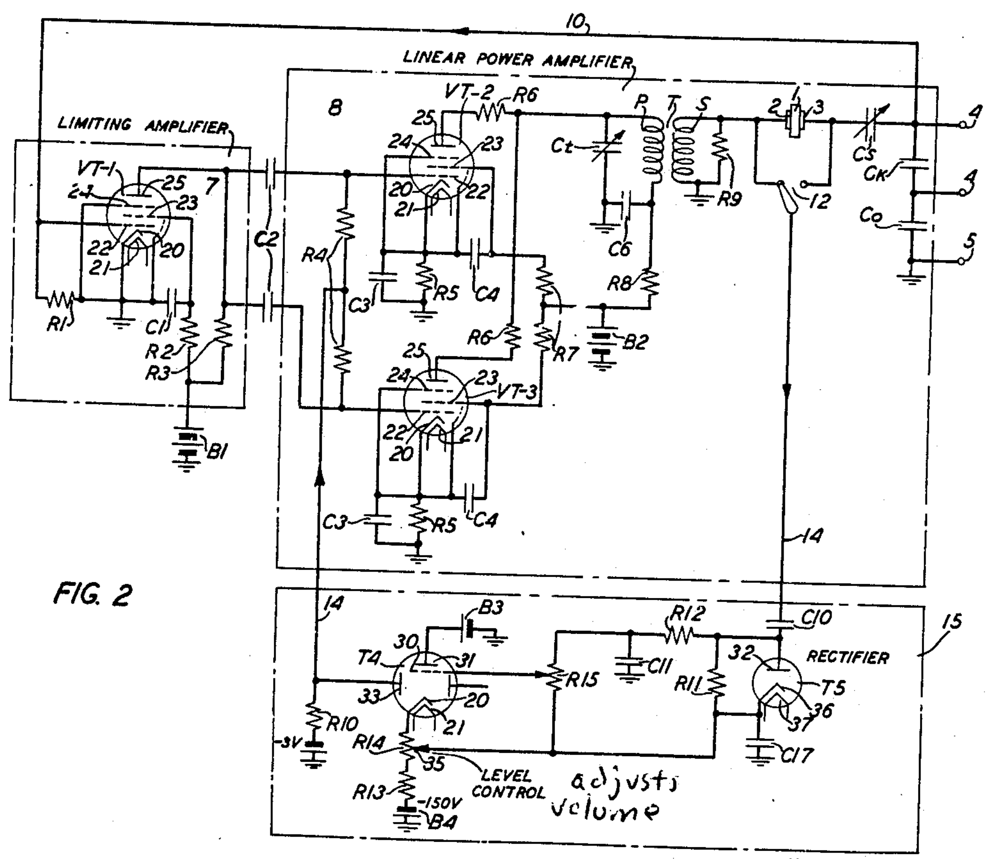

FIG. 2

tuning changes freq.

INVENTOR
C. W. HARRISON
BY W. J. O'Neill
ATTORNEY

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FIG. 3

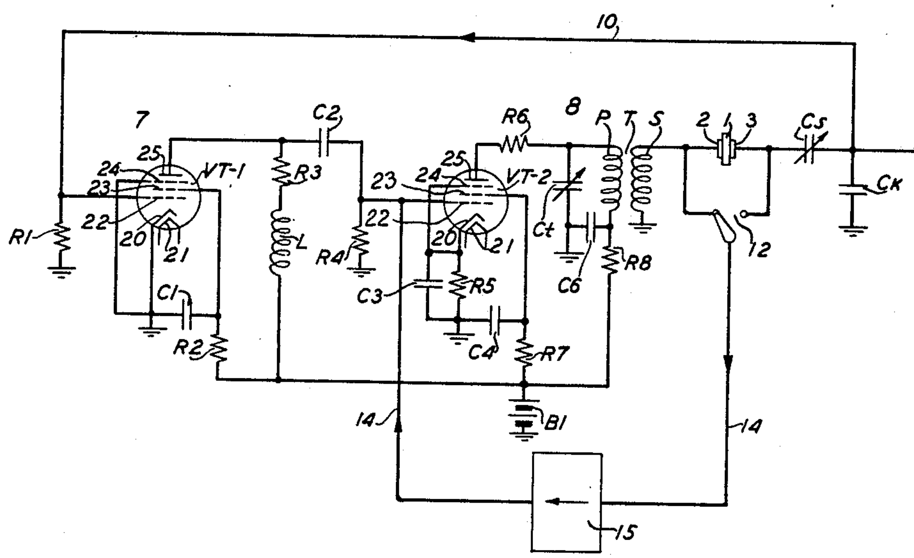
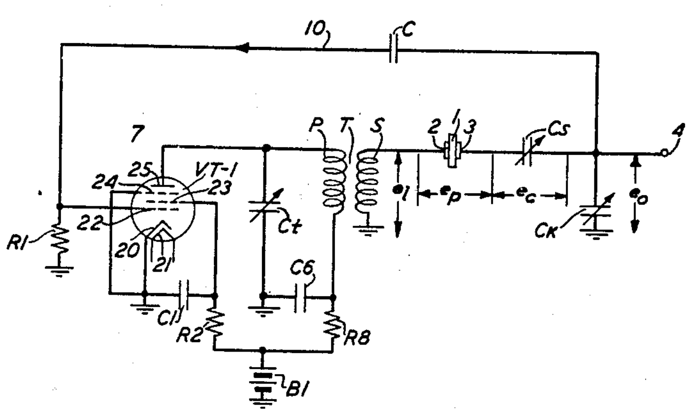


FIG. 4



INVENTOR
C. W. HARRISON
BY W. J. O'Neill
ATTORNEY

Patented June 29, 1948 2,444,349

UNITED STATES PATENT OFFICE

2,444,349

CRYSTAL OSCILLATOR CIRCUITS

Charles W. Harrison, Flushing, N. Y., assignor to Bell Telephone Laboratories, Incorporated, New York, N. Y., a corporation of New York

Application October 31, 1945, Serial No. 625,896

15 Claims. (Cl. 250—36)

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This invention relates to oscillation generators and particularly to constant amplitude crystal-controlled oscillation generator circuits. This application is a continuation in part of my copending application for Test circuit, Serial No. 576,659, filed February 7, 1945.

One of the objects of this invention is to improve the frequency and amplitude stability of oscillation generators.

Another object of this invention is to provide a tuning arrangement capable of selecting fine increments of frequency.

Another object of this invention is to provide a stable oscillator capable of utilizing high degrees of automatic amplitude control.

In accordance with this invention, a stable oscillator circuit may be provided which is adapted to overcome difficulties with "motor-boating," and which is capable of oscillating with even rather poor quality piezoelectric crystals, and capable of being adjusted over a wide voltage range to suit a great variety of different crystal elements that may be used in circuit therewith; and which is capable of maintaining its output voltage at a very constant amplitude level, and which may be provided with a tuning arrangement capable of selecting fine increments of frequency.

Oscillators in accordance with this invention may comprise an electronic amplifier, which may be either a limiting amplifier alone or a limiting amplifier followed by a linear amplifier, the amplifier apparatus being followed by a tuned step-down transformer connected across the output circuit of the amplifier, and a resonant crystal circuit comprising a series-connected piezoelectric element and capacitors connected across the secondary winding of the tuned transformer, and a feedback path extending from a point in the resonant crystal circuit to the input circuit of the limiting amplifier. In cases where the limiting amplifier and a separate linear amplifier are utilized, an automatic volume control circuit including a rectifier, a direct current amplifier and gain control means may be provided and designed with sufficient capacity to provide automatic amplitude control for the linear emplifier. The automatic amplitude control circuit may be arranged to have a time constant which is different from and somewhat slower than that of the limiting amplifier, in order to secure good output voltage stability free from "motor-boating." By "motor-boating" is meant a low frequency amplitude disturbance which is common to most forms of automatic amplitude-controlled

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oscillators. If desired, suitable shielding may be provided around the piezoelectric crystal body and also around the capacitors of the resonant crystal circuit, as disclosed in my parent application, Serial No. 576,659, hereinbefore referred to.

Oscillators in accordance with this invention may be utilized to develop a substantially constant voltage across the electrode terminals of the piezoelectric crystal element, independently of the quality of the crystal element over a quality range normally considered as usable in quartz crystal plates, and may be used as a basis for testing and for specifying the maximum voltage rating on various types of quartz crystal plates, as in the testing of such crystals during manufacture. To help in protecting such crystal elements against damage from an excessive voltage being accidentally applied across the terminals of the crystal element, it is useful to know the rating of the maximum surge voltage that the particular crystal element can withstand since the use in practice of a crystal element at voltages in excess of its maximum rated value or in excess of its proper working voltage often results in failure, due to internal heating and fracture of the crystal dielectric. Accordingly, it is often desirable that the manufacturer be able to supply piezoelectric crystals with a rating for the maximum surge voltage that the crystal element can be expected to safely withstand.

For a clearer understanding of the nature of this invention and the additional advantages, 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 diagram illustrating, in block diagram form, a constant-voltage, crystal-controlled, two-stage oscillation generator circuit provided with automatic amplitude control for the linear amplifier stage thereof;

Fig. 2 is a diagram illustrating, in schematic form, an oscillation generator circuit of the general type shown in Fig. 1;

Fig. 3 is a diagram illustrating a modification of the oscillation generator circuit shown in Fig. 2; and

Fig. 4 is a diagram illustrating a modification employing a single stage amplifier.

Referring to the drawing, Fig. 1 is a circuit diagram illustrating a two-stage, constant-voltage and constant-frequency oscillator, the frequency of which is controlled mainly by a suitable piezoelectric crystal element 1 having any suitable electrodes 2 and 3, and which is adapted to supply a substantially constant amplitude of output voltage e_0, at the output terminals 4 and 5 thereof. As illustrated generally by the block diagram labeled 7 in Fig. 1, the first amplifier stage 7 of the oscillator may comprise an amplifier 7 of the limiter type, the output of which is fed by suitable coupling means to the input of the second amplifier stage 8, which is illustrated generally by the block diagram 8 in Fig. 1. The second amplifier stage 8 may comprise a power amplifier of the linear type, the output of which is fed to the input circuit of a tuned transformer T having a primary winding P shunted by an adjustable tuning condenser Ct, and a secondary winding S which is shunted by a resonant crystal circuit comprising the series-connected piezoelectric crystal body 1 and condensers Cs and Ck. A feedback circuit 10 may supply output voltage e_0, from across the capacitor Ck to the input circuit of the limiting amplifier 7. A suitable switch 12 may be provided in an automatic amplitude control circuit 14 in order to supply voltage from either of the terminals 2 and 3 of the crystal element 1 to an automatic volume control system 15 which may comprise a rectifier and a direct current amplifier, the output of which is fed over the circuit 14 to the input circuit of the linear power amplifier stage 8.

The frequency of the oscillator illustrated in Fig. 1 is controlled mainly by the piezoelectric crystal element 1, through feedback from the capacitances of condensers Cs and Ck. The automatic volume control circuit 14 is provided in order that the amplitude of the voltage e_1 generated across the secondary winding S of the tuned transformer T may be held essentially constant at all times and at all frequencies. The circuit is constructed with component elements of values suitable for oscillation at the desired frequency, and an adjustment for insuring operation at the desired frequency is provided by the phase shifting network comprising the tuned transformer T having its primary winding P shunted by the variable tuning condenser Ct. By an adjustment of the tuning condenser Ct, the frequency of the circuit may be shifted the slight amount that may be necessary to obtain a suitable resonance corresponding to the resonant frequency of the crystal element 1. The ouput voltage e_0 appearing across the condenser Ck may be fed back and applied to the input circuit of the limiting amplifier 7.

The oscillator circuit illustrated in Fig. 1 is capable of oscillating when using any crystal body 1 that is usable in other types of oscillator circuits and, moreover, is capable of permitting high degrees of automatic volume control from the circuit 14 in order to maintain the generated voltage constant while adjusting the crystal circuit frequency for resonance operation. When the generated voltage is constant, resonance of the crystal circuit is essentially indicated by maximum crystal current, and oscillation is maintained at that resonant frequency. The adjustment to obtain maximum crystal current is such that the phase shift through the $\mu\beta$ oscillator loop is $2\pi n$ where $n=0, 1, 2, 3$, etc., the phase shift and resulting frequency of oscillation being varied by adjustment of the tuning condenser Ct associated with the tuned transformer T, and the magnitude of the generated voltage being held constant by the automatic amplitude control system 15 which may be similar to automatic volume control systems applied to amplifiers in radio systems. Manual control of the magnitude of the generated voltage e_1 may be provided by an adjustment of the bias voltage of the automatic amplitude control system 15 and in this way the maximum or start gain may be made independent of the setting of the amplitude control system 15.

The voltage e_1 may be, in some cases, generated by a single turn S of wire forming the secondary winding S of the transformer T, and the output voltage e_0 may be used as the feedback voltage supplied over the feedback circuit 10 to the input circuit of the limiter amplifier 7. The value of the voltage ratio of e_0/e_1 represents a voltage gain. This voltage gain is of course a fraction of the relative values of Cs and Ck. This type of oscillator circuit may present a pure capacity across the crystal element 1 for all frequencies equal to the value of

$$\frac{CkCs}{Ck+Cs}$$

Also, it may be operated over a wider reactance versus frequency range than earlier oscillators, with the amplitude of oscillation arbitrarily selected and held constant at that selected level and with high degrees of automatic amplitude control adjustable over a wide range.

While the limiter amplifier 7 and the linear amplifier 8 may be combined in a single tube amplifier as disclosed more fully hereinafter in connection with Fig. 4, the two are made separate when used with the automatic amplitude control rectifier and direct current amplifier 15, as illustrated in Figs. 1, 2 and 3. The application of the automatic volume control rectifier circuit 14 to this type of oscillator makes it desirable to separate the linear and limiter amplifiers 7 and 8 and to control the linear amplifier 8 slowly enough to permit the limiting amplifier 7 to absorb the changes in gain, thus damping out the critical transient caused by the automatic volume control rectifier 15, which maintains the output voltage constant with variable input to the power amplifier 8. In order to prevent "motor-boating," the time constant of the limiter amplifier 7 may accordingly be made faster than that of the automatic volume control system 15 especially for high degrees of automatic volume control provided by the circuit 14. It will be noted that such arrangement provides a stable amplitude control for the oscillator, with a tuning arrangement capable of selecting fine increments of frequency for the crystal circuit. A suitable low capacity diode type vacuum tube voltmeter (not shown) may, if desired, be used to indicate the voltage e_p across the crystal element 1. Since e_p is greater than e_1, the voltage across the crystal element 1 may be measured from the connection between the crystal element 1 and capacity Cs, and ground. The power supply system used may consist of any suitable supply voltage source or sources, which may be transformer sources adequately filtered and of conventional design.

Fig. 2 is a circuit diagram illustrating in schematic form an embodiment for the two-stage oscillation generator illustrated in block diagram form in Fig. 1. As illustrated in Fig. 2, the limiting amplifier 7 may comprise a suitable overloaded vacuum tube VT—1 giving a relatively flat response characteristic with a plate load of relatively low impedance, and the linear power amplifier 8 may comprise a single vacuum tube VT—2 or VT—3; or may comprise two parallel-connected vacuum tubes VT—2 and VT—3, such as type 6AG7 vacuum power tubes, the output of which is fed into the antiresonant primary winding circuit P of the tuned step-down transformer T, the secondary winding S of which provides a voltage e_1 which may be of low magnitude as compared to the voltage e_0 across the crystal electrodes 2 and 3.

The limiting amplifier 7 may be either of the overloaded variety or one whose output is limited by an automatic volume control circuit that operates only on that stage. In Fig. 2, the limiting amplifier tube VT—1 is shown as an overloaded vacuum tube stage 7 that drives the linear amplifier 8 at a constant peak level independently of the magnitude and variations of the output voltage e_0 over the range in which it is to be used. The linear amplifier 8 consisting of the two parallel-connected vacuum tubes VT—2 and VT—3 has its tuned plate circuit inductively coupled by the transformer T to the crystal circuit. The transformer T may be a step-down transformer T of the over-coupled unit type, wound, for example, on an iron dust toroidal coil form. The secondary winding S of the transformer T may consist of one or two turns of wire in a particular example, and may act as a generator to the crystal circuit. The crystal circuit may consist of a suitable piezoelectric crystal element 1 connected in series circuit relation with two series-connected capacitors C_s and C_k. The capacitor C_s may be variable, and the capacitor C_k may be fixed and the capacitance of the condenser C_k may be greater than that of the condenser C_s. The voltage e_0 developed across the condenser C_k or C_o, if used, may be fed back and used to excite the grid circuit 22 of the vacuum tube VT—1 of the limiting amplifier 7

The limiting amplifier 7 if of the overloaded variety may comprise a vacuum tube VT—1 having conventional electrodes which may, as illustrated in Fig. 2, comprise a grounded cathode 20 heated by a suitable cathode heater 21 energized by a suitable power supply source (not shown), a control grid electrode 22 connected through a suitable grid resistor R1 with the grounded cathode 20, a screen grid electrode 23 connected through a suitable screen grid resistor R2 with the positive (+) terminal of a suitable power supply source B1, a suppressor grid electrode 24 connected with the grounded cathode 20, and a plate electrode or anode 25 connected through a suitable plate resistor R3 with the positive (+) terminal of the plate supply source B1. The condenser C1 is a conventional by-pass condenser. The output of the limiting amplifier tube VT—1 may be fed from the plate electrode 25 thereof through one or more suitable coupling condensers C2 to the input circuit of the linear power amplifier 8.

The linear power amplifier 8 as particularly illustrated in Fig. 2 comprises two similar parallel-connected vacuum tubes VT—2 and VT—3 each provided with a cathode 20 connected to ground through a suitable parallel-connected cathode resistor R5 and condenser C3, control grid electrodes 22 interconnected through suitable grid resistors R4, screen grid electrodes 23 interconnected through suitable resistors R7 and connected through the resistors R7 with the positive terminal (+) of suitable power supply source B2, suppressor grid electrodes 24 connected with the cathodes 20, and plate electrodes 25 interconnected through suitable resistors R6 and connected with a suitable power supply source B2 through the resistors R6 and R8. The condensers C4 may be conventional by-pass condensers. The outputs from the anodes 25 of the linear power amplifier tubes VT—2 and VT—3 are connected across the input or primary winding P of the tuned transformer T.

As illustrated in Fig. 2, the transformer T has its primary winding P connected with the output circuits of the linear amplifier tubes VT—2 and VT—3 through the plate antising resistors R6, and the condenser C6. The secondary winding S of the transformer T is connected in circuit with the crystal element 1, and may, if desired, be shunted by a resistor R9. The transformer T may be a step-down transformer providing a relatively small voltage e_1 across the secondary winding S thereof. The output voltage e_1 generated across the terminals of the secondary winding S of the transformer T is maintained constant by means of the automatic volume control circuit 14 and is applied to the series resonant circuit comprising the piezoelectric crystal body 1 and the series-connected capacitors C_s, C_k and C_o. The condenser C_o may be omitted if desired. The transformer T has its primary winding P shunted by the tuning condenser C_t and is thereby adapted to adjust the resonance of the secondary winding S thereof and to provide a low impedance source of voltage e_1 across the secondary winding S of the tuned transformer T. Accordingly, the tuned transformer T functions as a phase shifter in the output circuit of the linear amplifier tubes VT—2 and VT—3 and may be utilized to adjust the resonant frequency of the oscillator by adjustment of the tuning condenser C_t. In addition, the tuned transformer T functions as an electric wave filter for filtering out undesired harmonics in the circuit.

The oscillator tubes VT—1, VT—2 and VT—3 provide current to the output circuit 4 through the transformer T and the oscillator is provided with automatic amplitude control comprising the automatic volume control rectifier and amplifier 15. The frequency of oscillation is under control of voltage derived from the crystal circuit comprising the piezoelectric crystal body 1 connected in series circuit relation with the series-connected capacitors C_s and C_k and the secondary winding S of the transformer T. The capacitors C_s and C_k divide the voltage in the series resonant crystal circuit and supply a voltage which may be fed back over the feedback circuit 10 to the input circuit of the limiter amplifier tube VT—1, in proper phase to maintain oscillations at the effective oscillating frequency, the frequency of oscillations being controlled mainly by the frequency of the crystal element 1, and the output voltage e_0 being under automatic amplitude control.

The tuning capacitor C_t may be adjusted for minimum impedance of the plate load of the linear amplifier tubes VT—2 and VT—3 in order to enable an incremental adjustment of the frequency of oscillation. The minimum impedance referred to may be indicated by maximum current through the circuit of the crystal element 1. In order to indicate such maximum current through the crystal circuit, a suitable direct current voltmeter (not known) may be used to measure the control voltage which the automatic volume control circuit 14 is applying to the control grids 22 of the linear amplifier tubes VT—2 and VT—3.

The resonant crystal circuit shunted across the secondary winding S of the transformer T comprises the piezoelectric crystal element 1 connected in series circuit relation with the capacitors Cs and Ck which are adapted to be adjusted to operate at the resonant frequency of crystal and capacitor circuit, and used as a means for developing an output voltage e_0 across the low impedance of the condenser Ck, to be supplied over the feedback circuit 10 to the input circuit of the limiting amplifier 7. The automatic amplitude control circuit 14 includes a rectifier the output of which is used as a control bias on the control grids 22 of the linear amplifier tubes VT—2 and VT—3. High degrees of automatic voltage control are possible with stability using this arrangement where the time constant of the limiting amplifier 7 is different from and preferably faster than the time constant of the automatic amplitude control circuit 14. By utilizing a direct current amplifier in the output of the rectifier 15 and by controlling more than one oscillator tube such as the tubes VT—2 and VT—3, very high degrees of automatic volume control may be realized, with stability of operation. By means of the switch 12, the voltage on either side 2 or 3 of the crystal body 1 may be held constant. Since the output voltage e_0 is developed across the relatively low impedance of the condenser Ck, and has been filtered twice, once by the tuned primary circuit P and Ct of the transformer T and second, by the resonant crystal circuit itself, the resulting output voltage e_0 is substantially free from electrical harmonics. The effective capacity across the crystal element 1 may be the same as the value of capacity in series with it when the condenser Ct is tuned for resonance. The capacity Ck forms a part of the series capacity in the resonant crystal circuit and may also be used as a means for adjusting the frequency of oscillation to exact resonance of the crystal circuit. The amplitude may be varied for a given crystal element 1 by adjusting the ratio of the capacitance of the condenser Cs with respect to the capacitance of the condenser Ck. As an example, if the voltage appearing across the crystal element 1 is needed to be held to a low value and still insure maximum sensitivity to start the oscillation thereof, the feedback voltage e_0 could be made to equal a greater portion of the sum of the voltages e_c and e_0 across the condensers Cs and Ck. In this way, the voltage across the crystal element 1 may be controlled at any frequency between the resonant and the antiresonant frequencies of the crystal element 1 at levels of voltage which may be, for example, less than 1.0 volt and at the same time stability and assurance of starting oscillations is obtained.

The crystal element 1 possesses two resonant frequencies, namely, a series resonant frequency which is determined by the effective inductance and the effective capacity thereof, and an antiresonant frequency which is determined by these quantities, plus the paralleling capacity which comprises the static capacity between the electrodes 2 and 3 of the crystal element 1 and any capacity connected thereto by the crystal holder and lead wires within the crystal holder. At frequencies other than the series resonant frequency, the paralleling capacity together with the associated shunt loss of the holder enters into determining the performance of the crystal element.

The piezoelectric crystal body 1 may resonate between its resonant and its antiresonant frequencies, and the impedance of the crystal element 1 operating within this frequency range appears as a positive impedance or in effect as an inductive reactance in series with a resistance. Any oscillator that operates the crystal element 1 in the positive region of the reactance versus frequency characteristic thereof exhibits capacity reactance and negative resistance paralleled across the terminals 2 and 3 to which the crystal element 1 is connected. The operation of the crystal element 1 when connected into the oscillator circuit will be influenced by the magnitudes of these two terms, and the combination will operate at such a frequency that the total reactance is zero and at such an amplitude that the total resistance is zero. The performance of the crystal element 1 will therefore not depend solely upon its own characteristics but will involve also the impedance of the remainder of the oscillator circuit associated therewith. The circuit of the oscillator provides an effective capacity which is composed of grid and lead wire capacities and capacity introduced from the plate circuit. The frequency at which this combination exhibits antiresonance is the oscillating frequency. Accordingly, oscillation of the crystal body 1 may take place at any frequency between its resonance and antiresonance frequencies with the appropriate selection for the capacitance values of the series condenser Cs or Ck. Also, this type of circuit will permit oscillation over a wide range of voltage operating amplitudes of the crystal body 1 as determined by the relation existing between capacitance values of the condensesr Cs and Ck. Thus, if the capacitance value of the condenser Ck is small and that of the condenser Cs is large, the amplitude of voltage across the crystal element 1 may be relatively low.

As hereinbefore mentioned and as shown in Fig. 2, automatic amplitude control, commonly referred to as automatic volume control or AVC, is applied to the linear power amplifier 8 comprising the vacuum tubes VT—2 and VT—3, which are separated from the limiter amplifier 7 comprising the vacuum tube VT—1. In order to apply a high degree of automatic amplitude control to the oscillator, the input voltage from the feedback circuit 10 to the vacuum tube VT—1 of the limiter amplifier 7 may be made above the threshold of limiting by an amount exceeding the variation in the β loop caused by the automatic amplitude control circuit 14, thereby to enable the limiter tube VT—1 to absorb the changes in the gain of linear amplifier tubes VT—2 and VT—3, such that $\mu\beta=1$ at all times. In order to permit damping of transients set up by the changes in gain occurring from the action of the automatic amplitude control circuit 14, the time constant of the limiter amplifier 7 including the tube VT—1 may be made fast compared to that of the automatic amplitude control circuit 14. The input of the linear amplifier including the vacuum tubes VT—2 and VT—3 is held constant by the action of the limiter amplifier 7 including the tube VT—1, and gain changes in the linear power tubes VT—2 and VT—3 due to variation of the capacitance of the tuning condenser Ct are absorbed by the automatic amplitude control circuit 14, while the variation of activity of the crystal element 1 is absorbed by the limiting amplifier tube VT—1.

The automatic amplitude control system 15 may comprise any suitable AVC rectifier and direct current amplifier. As illustrated in Fig. 2, the automatic amplitude control circuit 14 comprises conventional electron tubes T4 and T5. The tube T5 may comprise of a simple diode having a plate 32, a suitable cathode 36, and a filament 37, and which is coupled to the crystal circuit through a capacitor C10. The tube T5 is provided with a load resistor R11, a radio frequency grounded cathode 36 grounded through a capacitor C17, and a radio frequency filter comprising a resistor R12 and a capacitor C11, the arrangement being such that the voltage appearing across the capacitor C11 will be pure direct current. The second tube T4 has a cathode 20, a suitable cathode heater 21, a grid electrode 30, a plate electrode 31 connected with the positive (+) terminal of a suitable power supply source B3, a grid voltage control resistor R15 to determine the range of the level control, and a plate electrode 33 connected with the output circuit 14 leading to the input of the linear power amplifier 8 of the oscillator. The plate electrode 33 of the tube T4 is connected through a suitable resistor R10 to the initial bias potential for the vacuum tubes VT—2 and VT—3. The plate electrode 32 of the tube T5 is connected through a suitable resistor R11 to the cathode electrode 36, and through a resistor R12 and a condenser C11 to act as a filter. The cathode 20 of the tube T4 is connected to one side of the manual level control potentiometer resistor R14 which is connected in series with the load resistance R13, the resistor R13 being connected at its other end with the negative (—) terminal of a suitable power supply source B4.

The direct current amplifier portion of the tube T4 of the automatic level control system 15 applies a variable negative voltage to the control grids 22 of the vacuum tubes VT—2 and VT—3 of the linear amplifier 8, and is controlled by the signal voltage level of the circuit 14 which is rectifier by the rectifier T5, the resultant direct current voltage being applied to the grid electrode 30 of the direct current amplifier T4. As this latter voltage increases in value, the cathode 20 of the direct current amplifier T4 is driven negative with respect to the chassis ground G. The electrode plate 33 in the direct current amplifier tube T4 is then positive with respect to the cathode 20 and draws current, causing a negative voltage to appear across the load resistor R10. This negative voltage is applied over the circuit 14 to the control grids 22 of the linear amplifier tubes VT—2 and VT—3, thus reducing the gain of the linear amplifier stage 8. The voltage level point at which the control operates is the level at which the cathode 20 of the direct current amplifier T4 becomes negative with respect to the plate electrode 33, and this point may be varied by using the level control potentiometer R14 to apply an adjustable direct current voltage to the control grid 30 of the direct current amplifier T4. The grid electrode 30 of the tube T4 is connected to a resistance potentiometer R15 which determines the range of control possible by the level control R14.

Accordingly, in the automatic volume control system 15, the potential of the cathode 20 of the tube T4 may be varied in a negative direction by adjustment of the tap 35 of the potentiometer R14 in order to select the negative bias that determines the magnitude of the output voltage e_1 across the transformer secondary winding S controlled by the automatic volume control circuit 14, and thus permit the gain at starting to be a maximum, the bias then being a minimum at the time before the automatic volume control circuit 14 has any signal to operate on. Accordingly, this circuit may be expected to start and oscillate all piezo-electric crystals, capable of oscillation in other circuits. The crystal voltage e_0 may be almost a linear function of the rotation of a straight line type of potentiometer R14 used as the level control, which indicates that the direct current amplifier T4 may work on a linear portion of its plate current-grid voltage characteristic.

As mentioned hereinbefore, this oscillator is adapted to operate at any frequency between the resonance and antiresonance frequencies of the crystal element 1 and is capable of maintaining the output voltage e_0 constant when the tuning adjustment of the condenser Ct varies the frequency for maximum voltage. Moreover, this oscillator permits the control of some 30 decibels or more of automatic volume control at the operating level of the crystal element 1, and is free from amplitude disturbances for very high degrees of automatic volume control. When the time constant of the automatic volume control circuit 14 is made as fast as possible, greater stability of constant output may be obtained. Amplitude disturbances arise for the most part from the low frequency gain provided through the automatic volume control circuit 14 which may provide an additional β feedback loop and at some frequency the phase may be right to sustain an additional low frequency oscillation and thus cause the oscillator to oscillate at two frequencies simultaneously.

It will be noted that the high degree of automatic volume control may be accomplished in this oscillator by the separation and independence given the limiter amplifier 7 from the linear power amplifier 8, wherein the limiting action provided by the limiting tube VT—1 is above the threshold of limiting by an amount exceeding the variation in the β loop caused by the automatic volume control circuit 14 and the limiter 7 is thus enabled to absorb the changes in the gain of the linear amplifier 8. Moreover, the time constant of the limiter 7 may be made fast compared to that of the automatic volume control circuit 14 to permit the damping of transients set up by such changes in the gain that occur as a result of the operation of the automatic volume control circuit 14.

Fig. 3 is a circuit diagram of an oscillation generator similar to that shown in Fig. 2, except for the omission of one of the two vacuum tubes VT—2 and VT—3 from the linear amplifier 8 shown in Fig. 2. Accordingly, as shown in Fig. 3, the linear power amplifier 8 includes a single vacuum tube VT—2, and the circuit in other respects is similar to that shown schematically in Fig. 2.

As an illustrative example in a particular case, the resistance and capacitance and other values of the component elements of an oscillator circuit as illustrated in Fig. 3 of about 5 megacycles per second may be roughly as follows: resistor R1 about 470,000 ohms, resistor R2 about 33,000 ohms, resistor R3 about 1,000 ohms, inductance L about 20 microhenries, resistor R4 about 500,000 ohms, resistor R5 about 270 ohms, resistor R6 about 22 ohms, resistor R7 about 33,000 ohms, resistor R8 about 500 ohms, condenser C1 about .001 microfarad, condenser C2 about 50 micromicrofarads, condensers C3 and C4 about .001 microfarad each, condenser Ct about 0 to 100 micromicrofarads or other values to suit the circuit tuning, condenser C6 about .001 microfarad, condenser Cs about 0 to 100 micromicrofarads or other suitable value for tuning the circuit, and condenser Ck about 200 micromicrofarads. The limiting vacuum tube VT—1 and the linear type power tube VT—2 may be any vacuum tube suitable for such purposes. The crystal element 1 may be any suitable piezoelectric crystal element which for high frequencies may be a thickness-mode AT or BT cut quartz crystal element as disclosed for example in U. S. Patent No. 2,218,200, issued October 15, 1940, to Lack, Willard and Fair.

Fig. 4 is a circuit diagram of a crystal controlled oscillation generator using a single oscillator tube VT—1 functioning as a limiting amplifier. The vacuum tube VT—1 may be any suitable limiting type vacuum tube which provides some gain up to the region where the tube characteristic levels off. As illustrated in Fig. 4, the circuit comprises only one such oscillator tube VT—1. The crystal controlled oscillator in Fig. 4 comprises in addition to the limiting vacuum tube VT—1, the tunable transformer T, the crystal and condenser circuit in the secondary winding S of the tuned transformer T, and other component elements as hereinbefore described. A condenser C disposed in the feedback circuit 10 may be used to couple the output and input circuits of the vacuum tube V1. The condensers Cs and Ck may be used to divide the secondary circuit voltage and provide a reduced voltage in the feedback or β circuit 10, and for other purposes as described hereinbefore.

Accordingly, the oscillator circuit as illustrated in Fig. 4 comprises essentially the limiting amplifier 7 including the vacuum tube VT—1 followed by the tuned transformer T which may be a voltage step-down transformer T having a primary winding P shunted by the tuning condenser Ct, and having a secondary winding S shunted by the resonant crystal circuit which includes the piezoelectric crystal 1 connected in series circuit relation with the two capacitors Cs and Ck. The capacitor Cs may be adjusted to operate the circuit at the resonant frequency of the series-connected crystal element 1 and capacitor Cs. The capacitor Ck, also being part of the series capacitance in the resonant crystal circuit, may be used as a means for adjusting the frequency at oscillation to substantially exact resonance of the crystal circuit, and also it may be used to divide the circuit voltage and develop the output voltage e_0 across a relatively low impedance condenser Ck, to be used for feedback purposes as the input voltage to the control grid 22 of the limiting amplifier tube VT—1. As a result, the output voltage e_0, developed across the capacitor Ck has been filtered twice, once by the tuned primary winding P of the transformer T and again by the resonant crystal circuit itself, the result of such filtering being an output voltage e_0 which is relatively free from electrical harmonics. When the tuning condenser Ct is tuned for resonance, the effective capacitance across the crystal element 1 may be substantially the same as the value of capacitance in series with the crystal element 1. By adjusting the ratio of capacitance of the first condenser Cs with respect to that of the second condenser Ck, the amplitude of oscillations from a given crystal element 1 may be varied. For example, if it is desired to hold the voltage appearing across the crystal element 1 to a low value, and still insure maximum sensitivity to starting oscillations of the crystal element 1, the feedback voltage e_0 may be made to correspond to the greater portion of the sum of the voltage e_0 plus e_c appearing across both of the series-connected condensers Ck and Cs. In the extreme limit, the threshold of the limiting voltage applied to the control grid 22 of the limiting tube VT—1 may become e_0 plus e_c, and it may also be equal to the voltage appearing across the crystal element 1 since the crystal circuit is resonant, thus making the voltage across the inductance characteristic of the crystal element 1 equal to the voltage across the series capacitance characteristic thereof. In this way, the voltage across the crystal element 1 may be controlled at any frequency between the resonant and antiresonant frequencies of the crystal body 1, and at voltage levels down to a low value such as about one volt or less. At the same time, stability of operation and assurance of starting oscillations are of good quality.

The low level crystal oscillator circuit, as shown in Fig. 4, may be used for testing, or for aging of piezoelectric crystal elements 1, or wherever an oscillator circuit having low distortion output may be desired. This type of oscillator will permit the oscillation of piezoelectric crystals 1 at very low voltage levels, the start of oscillation is certain even with a voltage of the order of one volt applied across the crystal element 1, and this circuit will oscillate almost independently of the effective capacity across the crystal body 1, the equivalent shunt capacitor Ck being varied between 10 and 100 micromicrofarads for example.

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 is therefore not to be limited to the particular embodiments disclosed.

What is claimed is:

1. A crystal-controlled oscillation generator comprising electronic amplifier apparatus having input and output circuits, a tuned transformer having primary and secondary windings, said primary winding of said transformer being connected with said output circuit of said amplifier apparatus, a resonant crystal circuit comprising a piezoelectric crystal body, a first capacitor connected in series circuit relation with said crystal body, and a second capacitor connected in series circuit relation with said first capacitor and said crystal body, said resonant crystal circuit being connected with said secondary winding of said transformer, and a feedback circuit connected from a point intermediate said first and second capacitors of said resonant crystal circuit to said input circuit of said amplifier apparatus, said amplifier apparatus being provided with means for limiting and controlling the amplitude of said oscillation supplied to said output circuit.

2. A crystal-controlled oscillation generator comprising electronic amplifier apparatus having input and output circuits, a tuned transformer having primary and secondary windings, said primary winding of said transformer being connected with said output circuit of said amplifier apparatus, a condenser connected in shunt circuit relation with said primary winding for tuning said transformer, said tuned transformer constituting means for adjusting the frequency of said oscillation, a resonant crystal circuit comprising a piezoelectric crystal body, a first capacitor connected in series circuit relation with said crystal body, and a second capacitor connected in series circuit relation with said first capacitor and

said crystal body, said resonant crystal circuit being connected across said secondary winding of said transformer, and a feedback circuit connected from a point intermediate said first and second capacitors of said resonant crystal circuit to said input circuit of said amplifier apparatus, said amplifier apparatus being provided with means for limiting and controlling the amplitude of said oscillation supplied to said output circuit.

3. A crystal-controlled oscillation generator comprising electronic amplifier apparatus having input and output circuits, a tuned transformer having primary and secondary windings, said primary winding of said transformer being connected with said output circuit of said amplifier apparatus, a condenser connected in shunt circuit relation with said primary winding for tuning said transformer, said tuned transformer constituting means for adjusting the frequency of said oscillation, a resonant crystal circuit comprising a piezoelectric crystal body, a first capacitor connected in series circuit relation with said crystal body, and a second capacitor connected in series circuit relation with said first capacitor and said crystal body, at least one of said capacitors constituting means for adjusting the frequency of said oscillation, said resonant crystal circuit being connected across said secondary winding of said transformer, and a feedback circuit connected from a point intermediate said first and second capacitors of said resonant crystal circuit to said input circuit of said amplifier apparatus, said amplifier apparatus being provided with means for limiting and controlling the amplitude of said oscillation supplied to said output circuit.

4. A crystal-controlled oscillation generator comprising electronic amplifier apparatus having input and output circuits, a tuned transformer having primary and secondary windings, said primary winding of said transformer being connected with said output circuit of said amplifier apparatus, a resonant crystal circuit comprising a piezoelectric crystal body, a first capacitor connected in series circuit relation with said crystal body, and a second capacitor connected in series circuit relation with said first capacitor and said crystal body, said resonant crystal circuit being connected with said secondary winding of said transformer, and a feedback circuit connected from a point intermediate said first and second capacitors of said resonant crystal circuit to said input circuit of said amplifier apparatus, said tuned transformer and at least one of said first and second capacitors constituting means for adjusting the frequency of said oscillation between the resonance and antiresonance frequencies of said crystal body, said amplifier apparatus being provided with means for limiting and controlling the amplitude of said oscillation supplied to said output circuit.

5. A crystal-controlled oscillation generator comprising electronic amplifier apparatus having input and output circuits, a tuned voltage-step-down transformer having primary and secondary windings, said primary winding of said transformer being connected with said output circuit of said amplifier apparatus, a resonant crystal circuit comprising a piezoelectric crystal body, a first capacitor connected in series circuit relation with said crystal body, and a second capacitor connected in series circuit relation with said first capacitor and said crystal body, said resonant crystal circuit being connected with said secondary winding of said transformer, and a feedback circuit connected from a point intermediate said first and second capacitors of said resonant crystal circuit to said input circuit of said amplifier apparatus, said tuned transformer and at least one of said first and second capacitors constituting means for adjusting the frequency of said oscillation between the resonance and antiresonance frequencies of said crystal body, said amplifier apparatus being provided with means for limiting and controlling the amplitude of said oscillation supplied to said output circuit.

6. A crystal-controlled oscillation generator comprising a limiter amplifier having a voltage limiting characteristic, a separate linear amplifier comprising at least one vacuum tube having a substantially linear response characteristic, said linear amplifier having an input circuit connected with the output circuit of said limiter amplifier, a tuned transformer having primary and secondary windings, said primary winding of said transformer being connected with the output circuit of said linear amplifier, a resonant crystal circuit connected in shunt circuit relation with said secondary winding of said transformer, said resonant crystal circuit comprising a piezoelectric crystal body, a first capacitor connected in series circuit relation with said crystal body, and a second capacitor connected in series circuit relation with said first capacitor and said crystal body, a feedback circuit connected from said resonant crystal circuit to the input circuit of said limiter amplifier, and means including a rectifier connected from said resonant crystal circuit to said input circuit of said linear amplifier for controlling the amplitude of oscillation in said resonant crystal circuit.

7. A crystal-controlled oscillation generator comprising a limiter amplifier having a voltage limiting characteristic, a separate linear amplifier comprising at least one vacuum tube having a substantially linear response characteristic, said linear amplifier having an input circuit connected with the output circuit of said limiter amplifier, a tuned transformer having primary and secondary windings, said primary winding of said transformer being connected with the output circuit of said linear amplifier, a resonant crystal circuit connected in shunt relation with said secondary winding of said transformer, said resonant crystal circuit comprising a piezoelectric crystal body, a first capacitor connected in series circuit relation with said crystal body, and a second capacitor connected in series circuit relation with said first capacitor and said crystal body, a feedback circuit connected from said resonant crystal circuit to the input circuit of said limiter amplifier, and means including a rectifier and a direct current amplifier connected from said resonant crystal circuit to said input circuit of said linear amplifier for controlling the amplitude of oscillation in said resonant crystal circuit, the time constant of said last-mentioned amplitude control means being slower than the time constant of said limiter amplifier.

8. A crystal-controlled oscillation generator comprising a limiter amplifier having a voltage amplitude limiting characteristic, a separate linear amplifier comprising at least one vacuum tube having a substantially linear response characteristic, said linear amplifier having an input circuit connected with the output circuit of said limiter amplifier, a tuned transformer having primary and secondary windings, said primary winding of said transformer being connected with the output circuit of said linear amplifier, a resonant crystal circuit connected in shunt rela-

tion with said secondary winding of said transformer, said resonant crystal circuit comprising a piezoelectric crystal body, a first capacitor connected in series circuit relation with said crystal body, and a second capacitor connected in series circuit relation with said first capacitor and said crystal body, a feedback circuit connected from said resonant crystal circuit to the input circuit of said limiter amplifier, and means including a rectifier connected from said resonant crystal circuit to said input circuit of said linear amplifier for controlling the amplitude of oscillation in said resonant crystal circuit, the time constant of said last-mentioned amplitude control means being slower than the time constant of said limiter amplifier, said tuned transformer and at least one of said first and second capacitors constituting means for adjusting the frequency of said oscillation between the resonance and antiresonance frequencies of said crystal body.

9. A crystal-controlled oscillation generator comprising a limiter amplifier including an overloaded vacuum tube having a substantially flat response characteristic, a separate linear amplifier comprising at least one vacuum tube having a substantially linear response characteristic, said linear amplifier having an input circuit connected with the output circuit of said limiter amplifier, a tuned transformer having primary and secondary windings, said primary winding of said transformer being connected with the output circuit of said linear amplifier, a resonant crystal circuit connected in shunt relation with said secondary winding of said transformer, said resonant crystal circuit comprising a piezoelectric crystal body, a first capacitor connected in series circuit relation with said crystal body, and a second capacitor connected in series circuit relation with said first capacitor and said crystal body, a feedback circuit connected from a point between said first and second capacitors of said resonant crystal circuit to the input circuit of said limiter amplifier, and means including a rectifier connected from said resonant crystal circuit to said input circuit of said linear amplifier for controlling the amplitude of oscillation in said resonant crystal circuit, said tuned transformer and at least one of said first and second capacitors constituting means for adjusting the frequency of said oscillation between the resonance and antiresonance frequencies of said crystal body.

10. A crystal-controlled oscillation generator comprising a limiting type amplifier having an output circuit connected in tandem with and supplying oscillations to the input circuit of a separate linear type power amplifier, a transformer having primary and secondary windings, said primary winding being connected with the output circuit of said linear type amplifier, a series circuit comprising a piezoelectric crystal element, a plurality of series connected capacitors and said secondary winding of said transformer, said series circuit comprising the output circuit of said transformer, a feedback circuit connecting the output circuit of said series circuit with the input circuit of said limiting amplifier, and an automatic volume control circuit connected with and supplying rectified voltage from said output circuit of said transformer to said input circuit of said linear type amplifier, said limiting type amplifier comprising a relatively fast-acting limiter of the amplitude of said oscillations and said automatic volume control circuit comprising a relatively slower acting limiter of the amplitude of said oscillations.

11. A crystal-controlled oscillation generator comprising an amplitude limiting amplifier, a separate linear amplifier connected in the output circuit of said limiting amplifier, a phase-shifting tuned transformer having a primary winding connected with the output circuit of said linear amplifier, a series resonant circuit including a piezoelectric element and a capacitor and the secondary winding of said transformer, a feedback circuit connecting said series resonant circuit with the input circuit of said limiting amplifier, and automatic amplitude control means interconnecting the input and output circuits of said linear amplifier, the time constant of said limiting amplifier being faster than that of said automatic amplitude control means.

12. A crystal-controlled oscillation generator comprising a limiting non-linear type single-stage amplifier provided with means for limiting the amplitude of said oscillation, a tuned transformer having a primary winding and a secondary winding, said primary winding being connected across the output circuit of said limiting amplifier, a resonant crystal circuit shunted across said secondary winding of said transformer, said resonant crystal circuit comprising a piezoelectric crystal body connected in series circuit relation with a capacitor and an additional capacitor, said additional capacitor constituting means for adjusting the frequency of said oscillation to resonance in said crystal circuit and for developing an output circuit voltage across its impedance, and a feedback circuit connecting said output circuit voltage with the input circuit of said limiting amplifier.

13. A crystal-controlled oscillation generator comprising a limiting non-linear type amplifier, including an overloaded vacuum tube constituting means for limiting the amplitude of said oscillation, a tuned transformer having a primary winding and a secondary winding, said primary winding being connected with the output circuit of said limiting amplifier, a resonant crystal circuit shunted across said secondary winding of said transformer, said resonant crystal circuit comprising a piezoelectric crystal body connected in series circuit relation with a capacitor and an additional capacitor, said additional capacitor constituting means for adjusting the frequency of said oscillation to resonance in said crystal circuit and for developing an output circuit voltage across its impedance, and a feedback circuit connecting said output circuit voltage with the input circuit of said limiting amplifier, said transformer being a step-down transformer for supplying a reduced voltage to said resonant crystal circuit.

14. A crystal-controlled oscillation generator comprising a single-stage, voltage limiting non-linear type amplifier, a tuned transformer having a primary winding and a secondary winding, said primary winding being connected across the output circuit of said limiting amplifier, a resonant crystal circuit shunted across said secondary winding of said transformer, said resonant crystal circuit comprising a piezoelectric crystal body connected in series circuit relation with a capacitor and an additional capacitor, said additional capacitor constituting means for adjusting the frequency of said oscillation to resonance in said crystal circuit and for developing an output circuit voltage across its impedance, and a feedback circuit connecting said output circuit voltage with the input circuit of said limiting amplifier, said transformer being a step-down transformer for supplying a reduced voltage to said

resonant crystal circuit, and the ratio of the capacitances of said capacitor with respect to said additional capacitor being a value corresponding to the desired amplitude of oscillations of said crystal body.

15. A crystal-controlled oscillation generator comprising means for amplifying and limiting the amplitude of said oscillation, said means comprising a single vacuum tube having a substantially flat response overloaded characteristic, a tuned step-down transformer comprising primary and secondary windings and a tuning condenser disposed in shunt circuit relation with said primary winding, said primary winding being connected in shunt with the output of said limiting amplifier tube, a resonant crystal circuit connected in shunt with said secondary winding of said transformer, said resonant crystal circuit comprising a piezoelectric crystal element, a first capacitor connected in series circuit relation with said crystal element, and a second capacitor connected in series circuit relation with said first capacitor and said crystal element, and a feedback circuit connected from a point intermediate said first and second capacitors in said resonant crystal circuit to the input circuit of said limiting amplifier vacuum tube, said tuned transformer and one of said capacitors constituting means for adjusting the frequency of said oscillation between the resonance and antiresonance frequencies of said crystal element, and the ratio of the capacitances of said first and second capacitors being a value corresponding to the amplitude of oscillation of said crystal element.

CHARLES W. HARRISON.