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H-F CRYSTAL OSC

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It may be said, in general, that the high frequencies have lacked in large measure the benefit of good frequency stability as compared to the lower frequencies under approximately ten megacycles where crystal control has been usefully applied. Whether this stability was needed from the transmitter source or for the control of the receiver circuits, crystal control between ten and fifteen megacycles has been the useful fringe for the fundamental type of oscillator crystal.

When crystal control is thought of for use at frequencies up to one hundred megacycles and over, multiplier stages and buffer amplifiers must be used for the accomplishment of the higher frequency crystal stability desired. It would be an advantage to be able to obtain a source of crystal-controlled high frequency voltage without the use of additional, and costly, auxiliary intermediate stages.

Interference

In the future, this reduction in the number of radio-frequency multiplications generated for a given frequency multiple desired will be necessary for the elimination of spurious interference to received signals. For example, the use of pretuned channels in f-m and television receiving equipment will be most convenient and, with the wider band widths employed in this type of service, it may be very troublesome to have harmonics of the base oscillator interefere with a portion of the higher f-m and, especially, television carriers.

This thinking, of course, assumes that conventional crystal oscillator circuits and crystal plates are used for this purpose. It is logical to assume that the availability and economic structure of the production of crystal plates will allow the full consideration of equipment designed for their advantages. In any event, as the services are extended to the higher frequencies, the possibility of continuing to utilize standard self-excited oscillators does not yield the frequency stability requirement so important in the assignment and allocation of the additional services to be accommodated as time goes on.

Crystal oscillator circuits are usually considered rather straightforward items in design and not unusual or difficult propositions. And so they may be for the equipment and frequencies normally encountered in past experiences. However, certain fundamental problems must be considered for the use of crystals in circuits of higher frequencies. The chief differences are found in the method and manner of vibration of the crystal to be used in high-frequency control. At the same time it may be expected that the oscillator circuit itself will be modified to more suitably satisfy the reactances found at the higher frequencies.

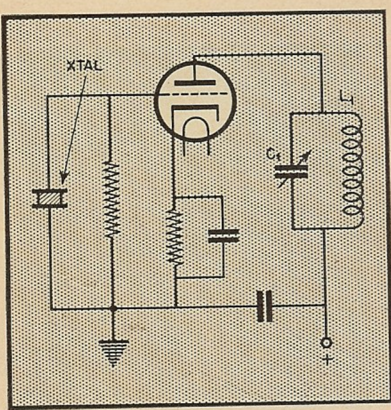

Fig. 1. Tuned plate crystal oscillator

Circuit Analysis

Fig. 1 illustrates a familiar crystal oscillator circuit in which the plate circuit elements *L1* and *C1* are arranged to vary the tuning of the fundamental frequency of the crystal element. *Fig. 2* illustrates the impedance network formed by the values associated in *Fig. 1* where

Z_{xtal}	is the effective impedance of the crystal at its resonant frequency.
E_{gc}	is the radio frequency voltage measured between the grid and cathode.

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ILLATOR CIRCUITS

An analysis of high-frequency crystal oscillator circuits is given. A special circuit for high harmonic operation is discussed.

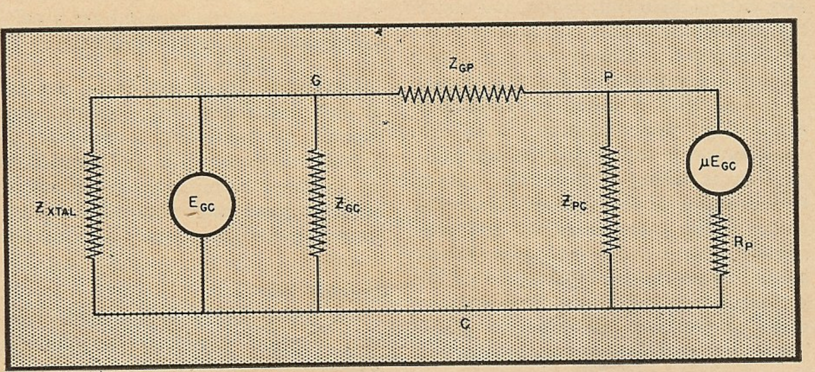

Fig. 2. Impedance network of tuned plate crystal oscillator.

Z_{gc}	represents the impedance of the circuit between the grid and cathode, consisting of the interelectrode capacity and circuit wiring. It should be noted that the impedance of the crystal is shown separately although it may be included with this value.
Z_{gp}	represents the grid-to-plate impedance.
Z_{pc}	is a measure of the plate-to-cathode impedance.
R_p	is the plate resistance of the tube.

The circuit shown is to be considered as operating in the class A region as an oscillator with E_{gc} and μE_{gc} essentially 180 degrees out of phase. As the value of *C1* is altered in *Fig. 1* a region will be approached where an inductive plate load will be presented to the resonant frequency of the oscillator grid circuit and may start oscillation in the crystal shown in the circuit. The impedance Z_{pc} will be relatively low compared to the value to be found associated with Z_{gc}.

The current I_{pc} will be found to lag μE_{gc} and E_{pc} will be equal to μE_{gc} minus $R_p\ I_{pc}$.

It can be seen that

$$\begin{aligned} & E_{pc} = E_{gc} + E_{pg} \\ \text{so} \quad & E_{gp} = Z_{gp}\ I_{gp} \\ \text{and} \quad & I_{gp} = I_{gc}\ Z_{gc} = E_{gc} \end{aligned}$$

When the plate circuit reactance is inductive, in this case Z_{pc}, and in the circuit shown, the coupling impedance Z_{gp} is capacitive, Z_{gc} will become a negative reactance and the effective resistance of the circuit looking from the crystal impedance will permit sustained oscillations to occur, provided the circuit parameters are so adjusted as to allow the proper phase relationship between E_{gc} and I_{pc} to be maintained.

At this point the crystal will assume control of the grid voltage and continue to vibrate alternately at the electromechanical frequency it has been designed for. The major electrical the dielectric capacity of the plate as well as the direct piezo-electric effect. The mechanical system, consisting of a discrete mass and stiffness, is electrically analogous to the inductance and capacity.

These are the useful crystal characteristics apart from the electrical equivalent conditions mentioned. This mechanical medium is coupled to the phase requirement of the oscillator proper through the piezo-electric coupling voltage generated by the potential supplied by the circuit. The value of this piezo-electric voltage in the circuit depends, in general, upon the method of mounting and exciting the crystal. Other variations, such as size and quality of the crystal and degree of skill used in the final adjustments, have a direct effect upon the worth of the crystal plate for high-frequency operation.

In *Fig. 3,* the piezo-electric coupling coefficient can be determined by the ratio of capacities given by

$$P = \frac{C3}{C1 + C2}$$

As the value of P diminishes the resonant frequency Fr and the anti-resonant frequency Fa will diminish in frequency separation also. See *Fig. 4.* This results in a smaller positive reactance region which will in turn limit the amplitude of the developed oscillator voltage.

Equivalent Circuit Values

In order to work intelligently with impedance values of the crystal element, a determination of the equivalent electrical values is in order. Equivalent circuit value measurements for a quartz crystal may be obtained by carefully following procedures of substituting values of known order in place of the crystal equivalent quantities. These electrical constants may be applied to the circuit analysis and permit a precise degree of planning for the design of crystal oscillator circuits. This will result in knowledge of the circulating crystal currents and the equivalent resonant frequency that will be obtained when a crystal of known electrical constants is used in the circuit.

The crystal manufacturer should be able to supply the equivalent circuit constants of his various units and thereby provide a set of values that are more easily coordinated with the equipment in which it must be used. This procedure will be ideal for matching exact frequency calibrations between circuits used at different locations and where carefully adjusted matched frequencies are required.

Measurements

For such measurements to mean much, the effects of crystal holders and associated mountings must be kept very uniform or variations of this type must be held to a minimum. The measurements can be obtained through the use of a variable radio-frequency energizing source from which the crystal under test is excited. The resonant frequency of the crystal is observed by checking the maximum deflection of a suitably connected vacuum tube voltmeter, used with a matching network as an indicating source of the resonant regions of the crystal plate. See *Fig. 5.*

The frequency of the crystal is measured and the vacuum tube voltmeter readings noted. The matching network may require a degree of adjustment depending upon the frequency of the crystal being measured as well as the type of associated components used in the crystal housing. A non-inductive variable resistance is substituted for the crystal at this point and adjusted to give the same vacuum tube voltmeter reading at the output of the network that existed with the crystal in the circuit. The measure of resistance obtained will be equivalent to the value $R1$ in *Fig. 3,* representing the equivalent circuit of a normally mounted quartz plate.

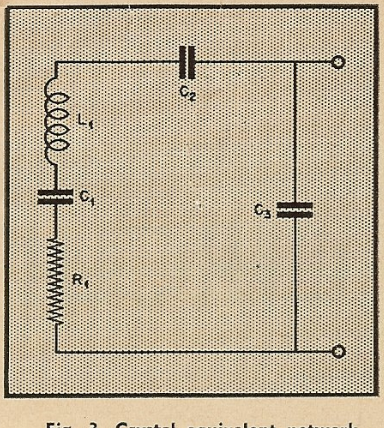

Fig. 3. Crystal equivalent network.

With the crystal replaced in the measuring circuit, a curve is now plotted of the exciting voltage value against frequency. The output voltage is maintained constant during these measurements. This measurement must be accurately plotted and preferably extend uniformly below and above the parallel and series resonance points. At this point, a known value of fixed capacity is substituted for the crystal in series with a value of resistance equal to $R1$ just measured. With this combination in the circuit the input excitation is adjusted until the output measurement of the vacuum tube voltmeter is the same value as that previously obtained with the crystal in position. From the curve obtained of input measurements versus frequency, a value of frequency is found at which the crystal reactance is equal to that of the substituted capacitor.

It is now possible to compute the equivalent circuit inductance of the crystal network. This is found from the following:

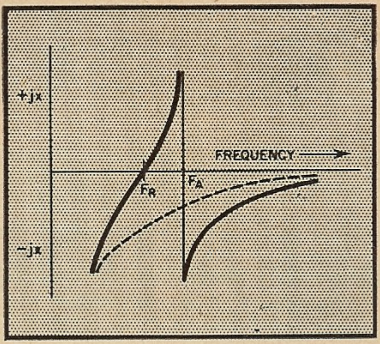

Fig. 4. Reactance of tuned circuit.

$$L = \frac{6Xc}{4\pi\ \Delta\ F}$$

Where Xc is the reactance of the substituted capacity at the measuring frequency, and F is the frequency increment as measured from the series resonant frequency Fr.

The crystal equivalent series capacity $C1$ is found from the formula

$$C1 = \frac{1\ Y}{(2\pi Fr)\ 2L}$$

The crystal shunt capacity $C3$ in series with the airgap capacity of the electrodes of the crystal unit are shunted across the equivalent crystal network. The crystal reactance will have a value given according to the following:

$$Xc = 4\pi\ \Delta\ F\ L$$

From the foregoing brief analysis of the functioning of a quartz plate capable of exhibiting a positive reactance necessary for the control of an oscillator circuit, this set of affairs becomes most important in the high-frequency harmonic type of crystal and circuit.

Crystal "Q"

The ability of the crystal to perform this function efficiently is generally referred to as the Q of the quartz plate. This may be computed from the following:

$$Q = \frac{1}{2\pi\ Fr\ C1\ R1}$$

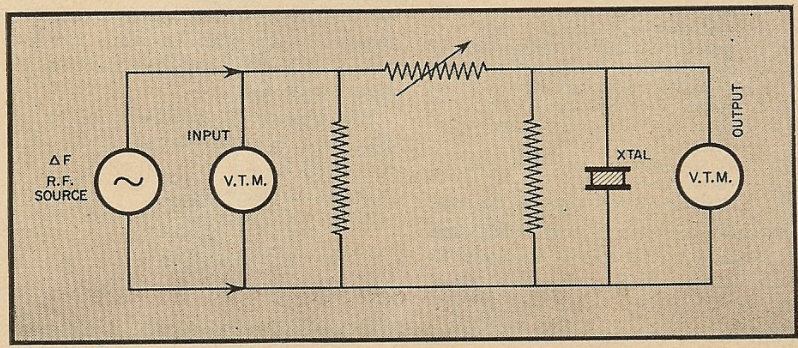

Fig. 5. Circuit for determining equivalent crystal values.

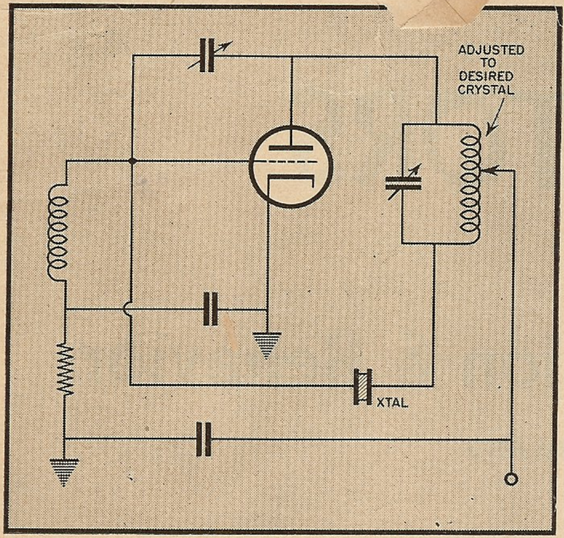

Fig. 6. Simple form of bridge oscillator circuit.

It has been shown by previous investigation (1) that it becomes increasingly difficult to excite the higher harmonic vibrations where a positive reactance of sufficient order is required to have the crystal assume control of the circuit. The limits involved may be shown as

$$\frac{P}{2} > \frac{1}{Q}$$

As explained the ratio of capacities found in the grid circuit divided by two must be greater in numerical value than the inverse quantity of the *Q*. In order to counteract the effect of the static shunt capacity *C3* across the crystal itself, which adversely affects the positive reactance desired, a different method of connecting the crystal to the oscillator circuit is resorted too.

See *Fig. 6*. A balanced network with equal impedances in the various branches, calculated against the crystal with its associated reactions, is the impedance balance required to reduce the shunting effect of *C3*.

With the effect of this value of capacity removed through a static balance of the capacities of the circuit, a positive crystal reactance may be obtained by careful adjustment of the oscillator circuit. At best, the value of *C3* is always the value of the associated shunt capacity, to a larger or smaller degree, depending upon the mounting characteristics of the crystal unit. Its reactance becomes increasingly less as the order of mechanical crystal harmonic increases.

It is at once apparent that in order to be able to use, for example, the fifteenth harmonic of a six-megacycle crystal plate it is necessary that the reactance of the components associated with the crystal be of an order that will permit the crystal to provide the necessary amount of control reactance. To perform this function, a crystal must be prepared with great care in the final grinding stages. The plane parallel surfaces must conform to a symmetry and polish that is unusually perfect in view of past technique.

Fig. 5 is a simple schematic diagram of a form of high-frequency bridge oscillator circuit. Its adjustment is critical although relatively simple with an active crystal. *L1* and *C1* are designed to resonate the fundamental frequency or the odd multiple frequencies of a thickness mode oscillator crystal. The voltage tap may be adjusted to the best position of balance determined by experiment and depending upon the physical construction of the oscillator circuit. For high frequency use it is just as important to follow compact design in the oscillator stage as would be considered for amplifier stages at these frequencies.

C3, in parallel with the plate and grid interelectrode and connected capacitances, is made adjustable so that this part of the circuit may be balanced against the crystal and holder reactances removed from resonance.

With the circuit in a balanced condition, no feedback is permitted until the tuned circuit is brought near the resonant frequency of the crystal. A disturbance of the balance through the introduction of a feedback voltage is possible at the sharply resonant frequency of the crystal.

Crystal Circuit for High Harmonic Operation

In *Fig. 7* an oscillator circuit is shown, as disclosed previously,* which is capable of driving a crystal at a high harmonic of its fundamental frequency. The necessary phase shift is introduced by the inductance arrangement and the resonant circuits are tuned so that their anti-resonant frequencies coincide with the resonant harmonic of the crystal. This is the condition for maximum output and stabilization against voltage changes.

In operation, the condenser balancing the crystal is turned off its balancing value and the circuit is allowed to oscillate uncontrolled by the crystal. The grid and plate tuned circuits are next adjusted until maximum output results near the desired crystal frequency. The balancing condenser is then adjusted toward balance and the oscillation will usually stop.

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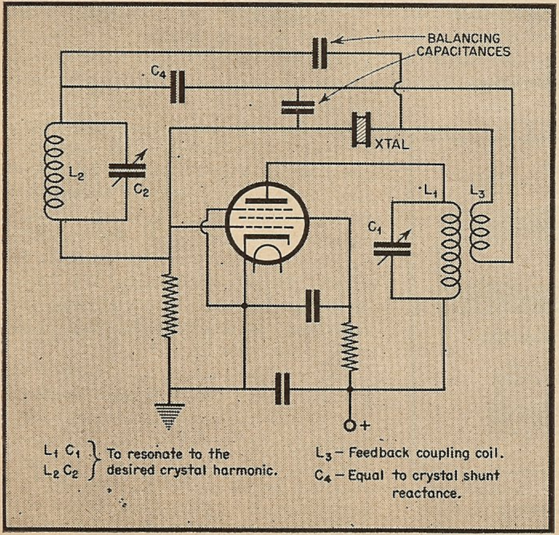

Fig. 7. Bridge circuit for high harmonic excitation. The balancing capacities and C4 are low values of capacitance; for best performance, under 5 to 10 $\mu\mu f$.