CHAPTER 5
FREQUENCY STANDARDS

1. INTRODUCTION

Because frequency is defined in terms of cycles per second or events per unit time, frequency control and timekeeping are inseparable. Any measurement of frequency can be only as accurate as the time unit used. Thus in order to determine the accuracy of a frequency standard, its period of oscillation must be compared to a time standard of known accuracy. The best secondary time standard consists of a frequency standard which drives a cycle counter or clock. The accuracy of this time standard can be then determined by comparing it with the primary time standard which is the mean solar day, that is, the time required for the earth to complete one revolution about its axis.

Time measurement has always been based on astronomical phenomena. Days and years are determined by the relative motion of the earth with respect to the sun. However, to co-ordinate events and to make precise measurements of physical phenomena, a device that can divide the day into accurate, shorter intervals is required. The search for accurate timing devices started in prehistoric time. It followed two separate lines: first, those devices which derive time directly from astronomical observations; and second, independent mechanisms and devices for measuring time intervals. The first type started with the casual observation of the position of the sun, progressed to the sundial, and culminated in the modern Zenith tube. The second type started with devices based on restricted flow. The first of these were the noncycling types, such as the sand clocks, water clocks, time candles, and time lamps. Typically, sand clocks or hourglasses had inaccuracies of 4,000 seconds per day. These were followed by automatic recycling types using escapement mechanisms controlled by friction and inertia, such as the Verge and Foliot balance. Clocks of this type varied 1,000 seconds per day. With the discovery of resonance phenomena, that is, an oscillating system in which energy is alternately stored in the form of kinetic and potential energy, much more accurate time measurements were made possible. The first device using resonance phenomena to measure time was the pendulum clock which ultimately attained an accuracy of .002 second per day. The pendulum was followed by the hairspring and balance which attained an accuracy of .2 second per day, and the electrically activated tuning fork which attained an accuracy of .008 second per day. The quartz crystal, which followed the tuning fork as the resonator in time and frequency standards, has an accuracy of 1 part in 10^9 per day or .0001 second per day and is the most widely used control element in modern time and frequency standards. Due to variations in the rotation of the earth, the short-term accuracy of the quartz crystal is better than that of the mean solar day. Seasonal variations of several milliseconds and yearly variations as great as 1.6 seconds in the mean solar day have been observed. On a long-term basis, however, the length of the mean solar day is increasing at the rate of only .00164 second per century. In order to achieve long-term accuracy, the standard must remain in constant operation; and since mechanical devices such as the quartz crystal clock will run for only a few years, they will probably not replace astronomical phenomena as a primary time standard. The most recent development is the use of devices based on atomic or molecular resonance. These have attained short-term accuracy equal to that of the quartz crystal, but their long-term accuracy is expected to be considerably better.

Technical and economic forces have led to the development of more and more accurate frequency control circuits. In the early days of radio, the tunable LC oscillator provided a simple and serviceable answer to the problem of generating channel frequencies. The lower frequency end of the spectrum and amplitude modulation were used, and the spectrum was not unduly crowded. Later crowding of the spectrum led to closer channel spacing and expansion into the higher frequency regions. This in turn required more accurate frequency control. Crystal oscillators provided the required accuracy, but many crystals were required to provide the required number of channels. During World War II, it became almost impossible to deliver the right crystal to the right place at the right time. After the war, users of communication equipment demanded a choice of hundreds of channels at the flick of a switch. In order to meet the demand for spectrum space, guard bands were narrowed, and the vhf bands were put to more extensive use. All of these forces led to the development of the multiple-crystal frequency synthesizer (figure 5-1) in which the output frequencies of several crystal oscillators were mixed together to produce the desired output frequencies, providing many more channels than the number of crystals used. Present crowding of the spectrum and increasing demand for communication channels now indicate that some method of further decreasing the spectrum space required for each channel must be found. Single sideband is a solution to this problem. The use of single

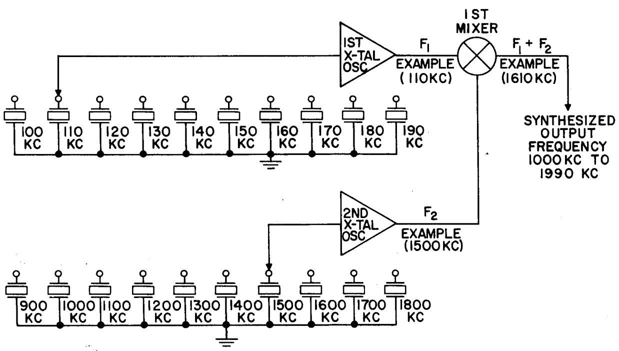

Figure 5-1. Multiple-Crystal Frequency Synthesizer

sideband, however, requires that channel frequencies be maintained within ±1/2 part per million. Maintaining all of the crystals in a multiple-crystal synthesizer to the required accuracy is impractical; therefore, all the stability requirements must be concentrated in one or, at the most, several highly stable oscillators. The solution to this problem is the single-crystal frequency synthesizer. Figure 5-2 is a block

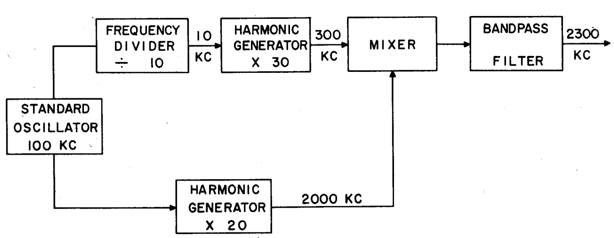

Figure 5-2. Single-Crystal Frequency Synthesizer

diagram of a typical single-crystal frequency synthesizer. Basically it is a circuit in which harmonics and subharmonics of a single standard oscillator are combined to provide a number of output signals which are all harmonically related to a subharmonic of the standard oscillator. In this system the accuracy and stability of the output signals are equal to that of the standard oscillator and as techniques improve, the stability of the synthesizer can be improved by replacing only the standard oscillator.

The best laboratory standards now available have aging rates of approximately 1 part in 10^9 per month and short-term variations of several parts in 10^{11}. Operational standards have several orders of magnitude greater instability. Typical examples are shown in the curves of figures 5-3 and 5-4. In figure 5-3, the dots represent errors derived from direct time comparison with WWV, and the crosses represent errors derived from time comparison with WWV after correction according to WWV's time correction bulletin.

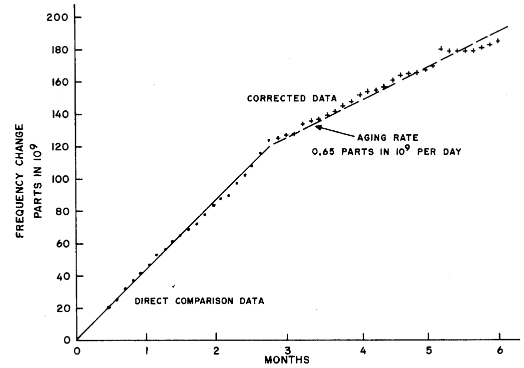

Figure 5-3. Typical Long-Term Stability

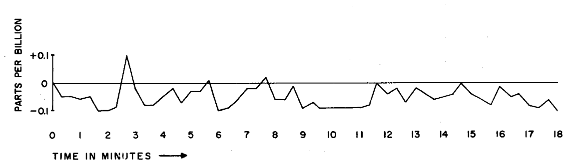

Figure 5-4. Typical Short-Term Stability

2. DETERIORATION OF GENERATED FREQUENCY

Although frequency standards in use today have accuracies of 1 part in 10^8 or better, serious errors can be introduced in the transmission and reception of the signal. These errors are caused by Doppler shift, shifts due to propagation characteristics, and shifts due to equipment circuitry.

a. EFFECT OF DOPPLER SHIFT

Relative motion between receiving and transmitting stations causes premature or delayed reception of individual cycles of the transmitted signal. Since the speed of propagation of radio signals is equal to the speed of light or 186,000 miles per second, cycles of the transmitted signal will be received 1 millisecond earlier or later for every 186 miles of change in transmission path length. A change in transmission path length at a rate of 670 miles per hour results in a frequency shift due to Doppler effect of 1 part in 10^6. Figure 5-5 shows an aircraft approaching a radio transmitter. In the formula shown in the figure, v = velocity of the aircraft and C = speed of light. If the aircraft is approaching at a velocity of 670 miles per hour or 0.186 miles per second, then the ratio v/C = 0.186/186,000 or 1/1,000,000. Thus the ratio of frequency change to transmitted frequency ($\Delta f/f$) is $1/10^6$. If the transmitter is operating on a frequency of 10 mc, then the frequency as received at the aircraft will be 10 mc plus 10 cps. If the transmitter were also in an aircraft flying toward the first aircraft at a velocity of 670 miles per hour, the frequency error would be doubled because the relative velocity would be the sum of the velocities of the two aircraft or 1,340 miles per hour. In ship to ship communication or in communication between ground vehicles, Doppler shifts of 1 part in 10^7 or greater are possible. Doppler shifts due to antenna sway caused by the pitch and roll of a ship are of the order of ±3 parts in 10^9. Extreme examples of Doppler shift are the case of back-pack radios in which the Doppler shift while the operator is walking is 5 parts in 10^9, and the case of the IGY satellite, where signals transmitted by the satellite will suffer frequency shifts of up to 30 parts per million. Signal transit time in the case of a jet aircraft traveling 670 miles per hour and communicating with a fixed station changes at the rate of 3.5 milliseconds per hour, and in the case of battleships communicating with each other the signal transit time can change 0.2 milliseconds per hour.

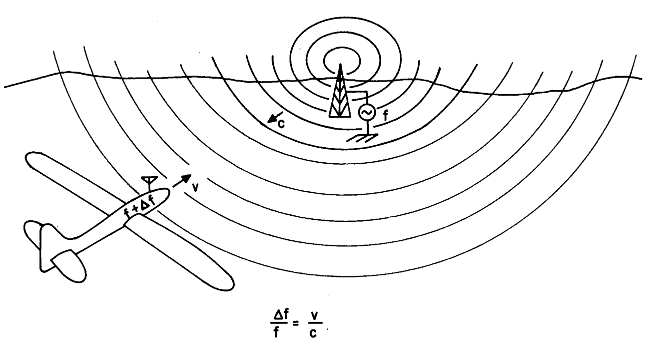

Figure 5-5. Doppler Frequency Shift in Aircraft

b. EFFECT OF PROPAGATION CHARACTERISTICS

Low-frequency waves tend to follow the curvature of the earth, and the length of the transmission path is not seriously affected by atmospheric or ground conditions. Errors introduced by the propagation medium at low frequencies are only about ±3 parts in 10^9 in frequency and ±40 microseconds in transit time. In the high-frequency bands, however, reflections from the ionosphere are used for long-range communications. Frequency variations of ±2 parts in 10^7 and transit time variations of ±1 or 2 milliseconds can be introduced by changes in path length due to movement of the reflection point in the ionized layer and variations of the skip distance. Errors introduced in vhf and uhf scatter propagation are not well known, but available data indicate that they may be several parts in 10^8 in frequency and several hundred microseconds in transit time.

c. EFFECTS OF EQUIPMENT CIRCUITRY

Transmitter or receiver circuit elements when subjected to mechanical vibration or temperature changes can cause temporary frequency shifts by temporarily shifting the phase of the signal. Phase advancement of 360 degrees in one second adds 1 cycle per second to the frequency of a signal. Thus, a phase shift change of 1 degree per second imposed on a 100 kilocycle signal would cause a temporary frequency shift of 3 parts in 10^8. Mechanical vibration of tuning elements causes phase shifts which even under laboratory conditions may cause frequency shifts as great as 1 part in 10^8. Under operating conditions severe mechanical vibration and temperature changes may be encountered which, if not compensated for, would cause excessive frequency errors. Therefore, in precision work, mechanically rigid components must be used in all tuned circuits.

3. MEASUREMENT TECHNIQUES

a. TIME COMPARISON

Accurate comparisons of time and frequency using radio communication are difficult because of variations in propagating mediums. Present methods are based on time measurements taken over a long period so that these variations average out. By taking time measurements from WWV over a period of 20 days, accuracies of 1 part in 10^9 can be attained in the 2 mc to 30 mc bands. At 16 kc, the same accuracy can be attained in approximately one day because the variations in the propagating medium have less effect on the low-frequency signal. Figures 5-6 and 5-7 are block diagrams of time comparison systems suitable for fixed station use. On shipboard errors introduced by changes in signal transit time due to relative motion between stations must be taken into account to achieve the same accuracies as are attained in fixed station use.

Figure 5-6 shows a system using an aural indication of synchronization of a clock, controlled by a local oscillator, with the time signals transmitted by WWV. The oscillator operates at 100 kc; this frequency is divided by 100, and the resulting 1000 cps signal operates the synchronous clock. The clock operates a switch which closes once each second. A receiver tuned to WWV's signal is used to detect the

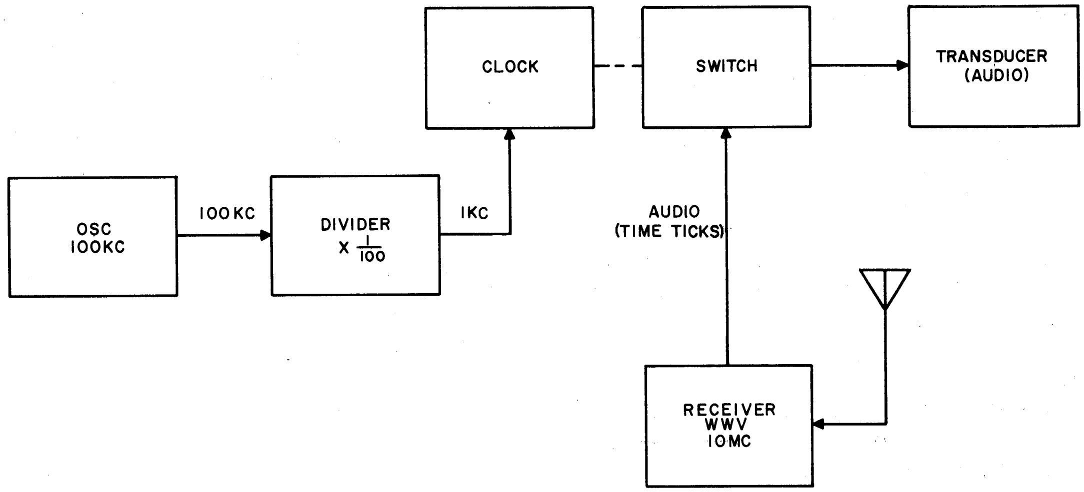

Figure 5-6. Time Comparison System, Aural Indication

time signals which are in the form of clock ticks. These clock ticks consist of 5 cycles of a 1000 cps tone, transmitted at the rate of one tick per second. The ticks are coupled to a loud-speaker through the clock operated switch which can be adjusted to close each time a tick is received. Once adjusted, the switch will continue to close in synchronism with the reception of the clock ticks as long as the frequency of the oscillator remains exactly 100 kc. If the oscillator frequency changes, the speed of the clock will also change, and the switch closures will slowly drift out of synchronization. A calibrated dial is used to adjust the synchronization of the switch daily to permit only the last cycle of the clock tick to pass. The stability of the oscillator can be determined to an accuracy of 12 parts in 10^8 by calculations based on the amount of adjustment required in one day. The accuracy of measurement can be increased to 1.2 parts in 10^9 by basing the calculations on the amount of adjustment required in a period of 100 days.

Figure 5-7 is a block diagram of a chronoscope. The 100 kc signal from the oscillator is divided to 10 cps and applied to the vertical and horizontal plates of the cathode-ray tube through phase shifting networks to produce a circular trace on the scope screen. A 1

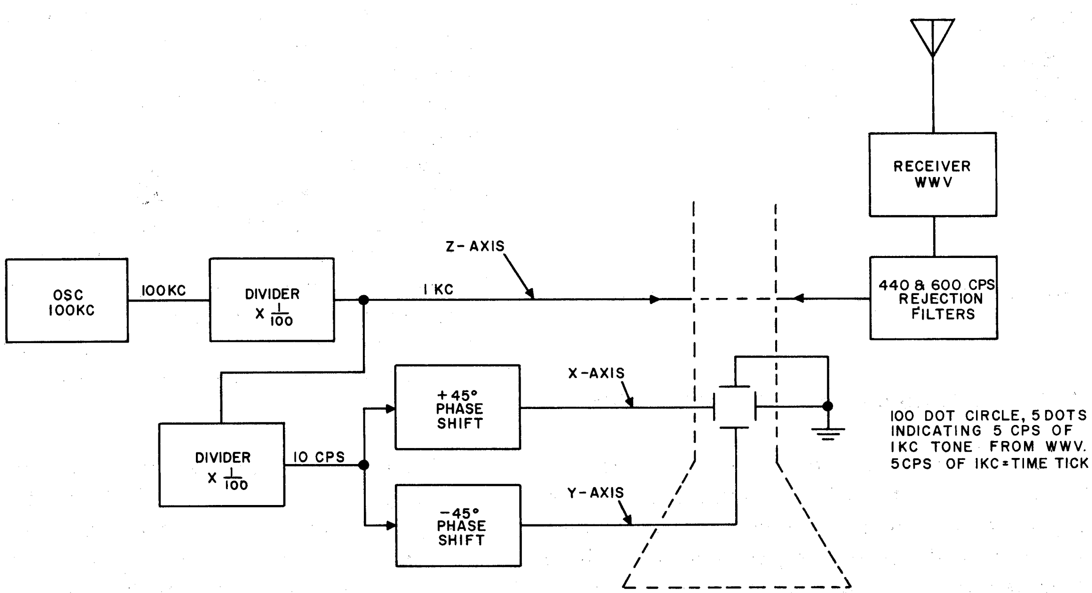

Figure 5-7. Time Comparison System, Visual Indication, Chronoscope

kc signal derived from the same oscillator is applied to the intensity control grid to break this solid circle into 100 dots. A receiver tuned to WWV supplies the clock ticks to the same control grid producing five additional dots somewhere on the 100 dot circle depending upon the relative phase of the 1 kc signal from the oscillator and the 5 cycles of 1 kc which comprise the clock tick. If the phase relationship remains constant, the 5 dot pattern on the screen will remain fixed; but if the phase changes, the pattern will move around the 100 dot circle at a rate determined by the rate of phase change. The rate of movement in turn indicates the magnitude of frequency error. With this system the frequency of the oscillator can be determined to an accuracy of 1.2 parts in 10^8 in one day or 1.2 parts in 10^9 in 10 days.

b. FREQUENCY INTERCOMPARISON

Short-term stabilities of oscillators can be determined by intercomparison of the frequencies of two or more oscillators. When only two oscillators are compared, only the relative stabilities of the oscillators with respect to each other can be determined. Statistical data which will indicate the short-term stability of an individual oscillator can be obtained by intercomparing the frequencies of three or more oscillators two at a time.

Figure 5-8 illustrates a system using two oscillators operating at frequencies differing by, nominally, 1 cps. One oscillator operates at 1 mc, and the other operates at 1 mc plus 1 cps.

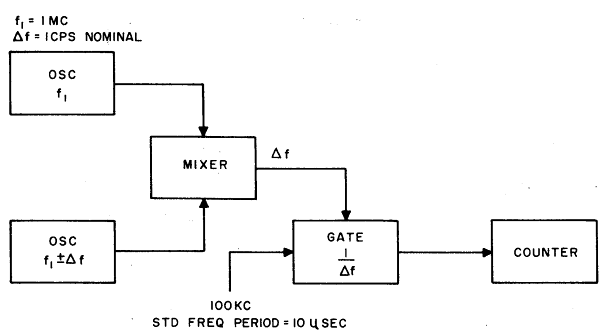

Figure 5-8. Frequency Intercomparison System Using Frequency Counter

Their outputs are mixed and the difference frequency, 1 cps, is used to control a gate circuit. A 100 kc standard frequency is applied to the gate and the number of cycles of this standard frequency which are counted at the output indicates the length of time the gate is open. This in turn is the period of the difference frequency controlling the gate. Thus if the difference frequency is exactly 1 cycle per second, the gate will be open exactly 1 second, and the counter will count exactly 100,000 cycles. If the difference frequency is more than 1 cycle per second, the counter will count less than 10^5 cycles, and if the difference frequency is less than 1 cycle per second, the counter will count more than 10^5 cycles. This system will indicate the relative stability of one oscillator with respect to the other to 1 part in 10^{11}.

Figure 5-9 illustrates a system using two oscillators adjusted to operate at frequencies differing by 0.6 cps. The frequency of each oscillator is multiplied by 100 before mixing so that the resultant beat note is 60 cps. This beat note is recorded on a power line frequency recorder to give a continuous indication of relative stability between the two oscillators with an accuracy of 5 parts in 10^{10}.

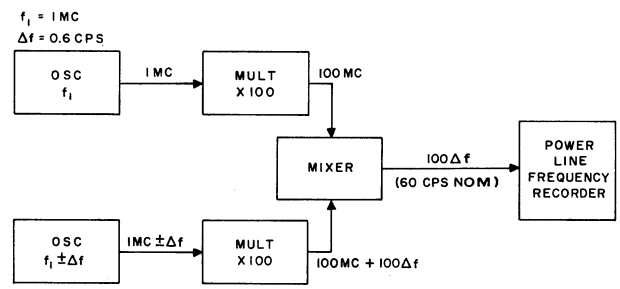

Figure 5-9. Frequency Intercomparison System Using Power Line Frequency Recorder

c. PHASE INTERCOMPARISON

Figure 5-10 illustrates a system wherein the relative phase of two oscillators operating at the same frequency is measured. If the relative phase as indicated by the phase comparison meter changes 360 degrees in one second, then the difference in frequency of one oscillator with respect to the other is 1 cps;

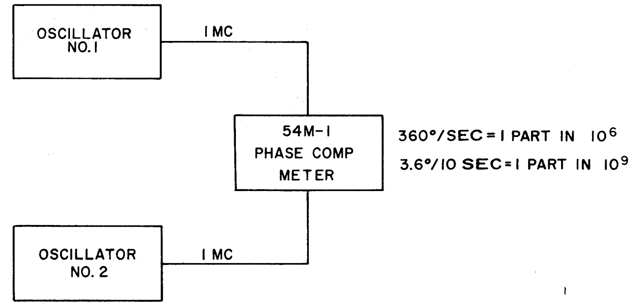

Figure 5-10. Phase Intercomparison System

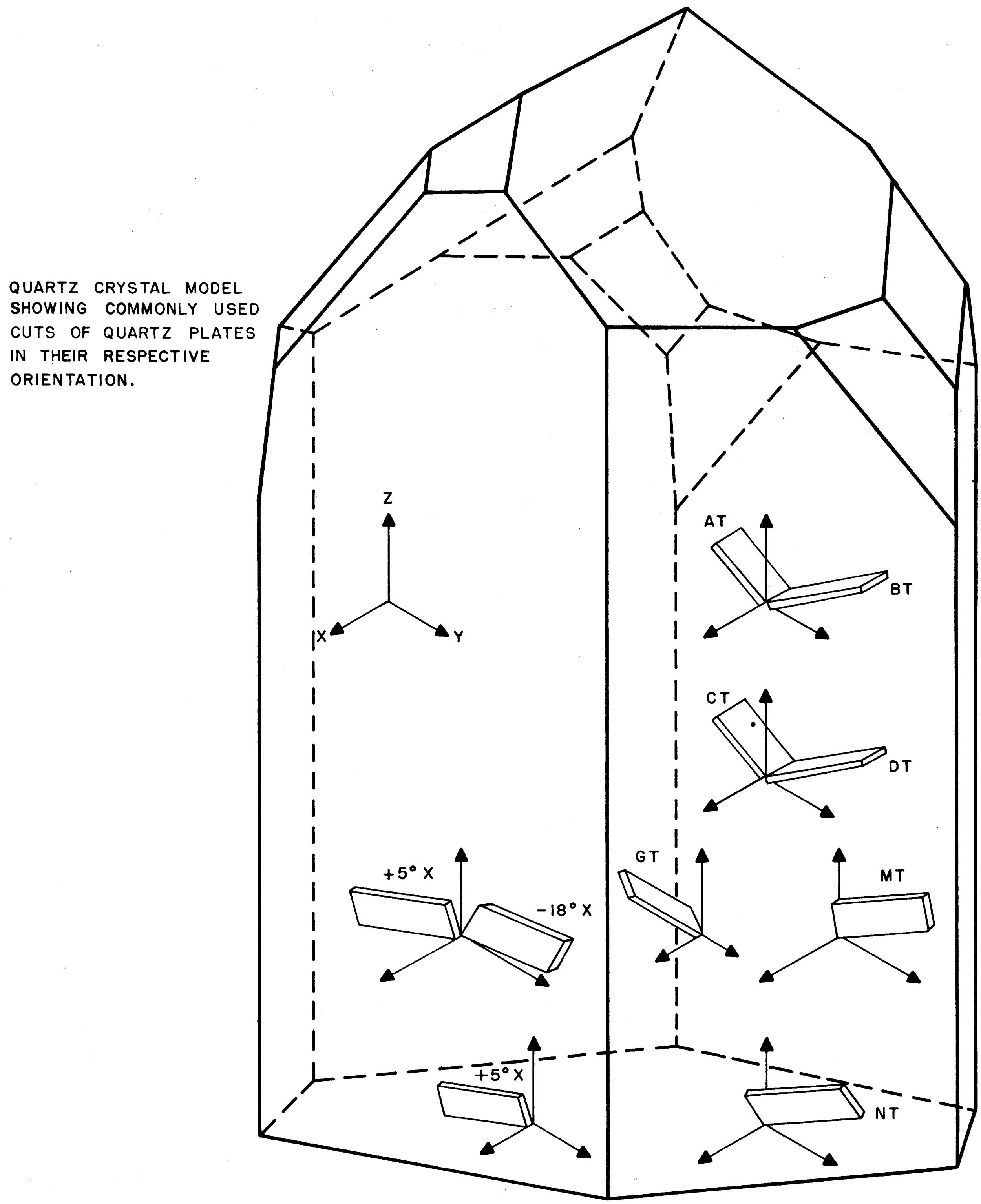

Figure 5-11. Quartz Crystal Showing Types of Cuts

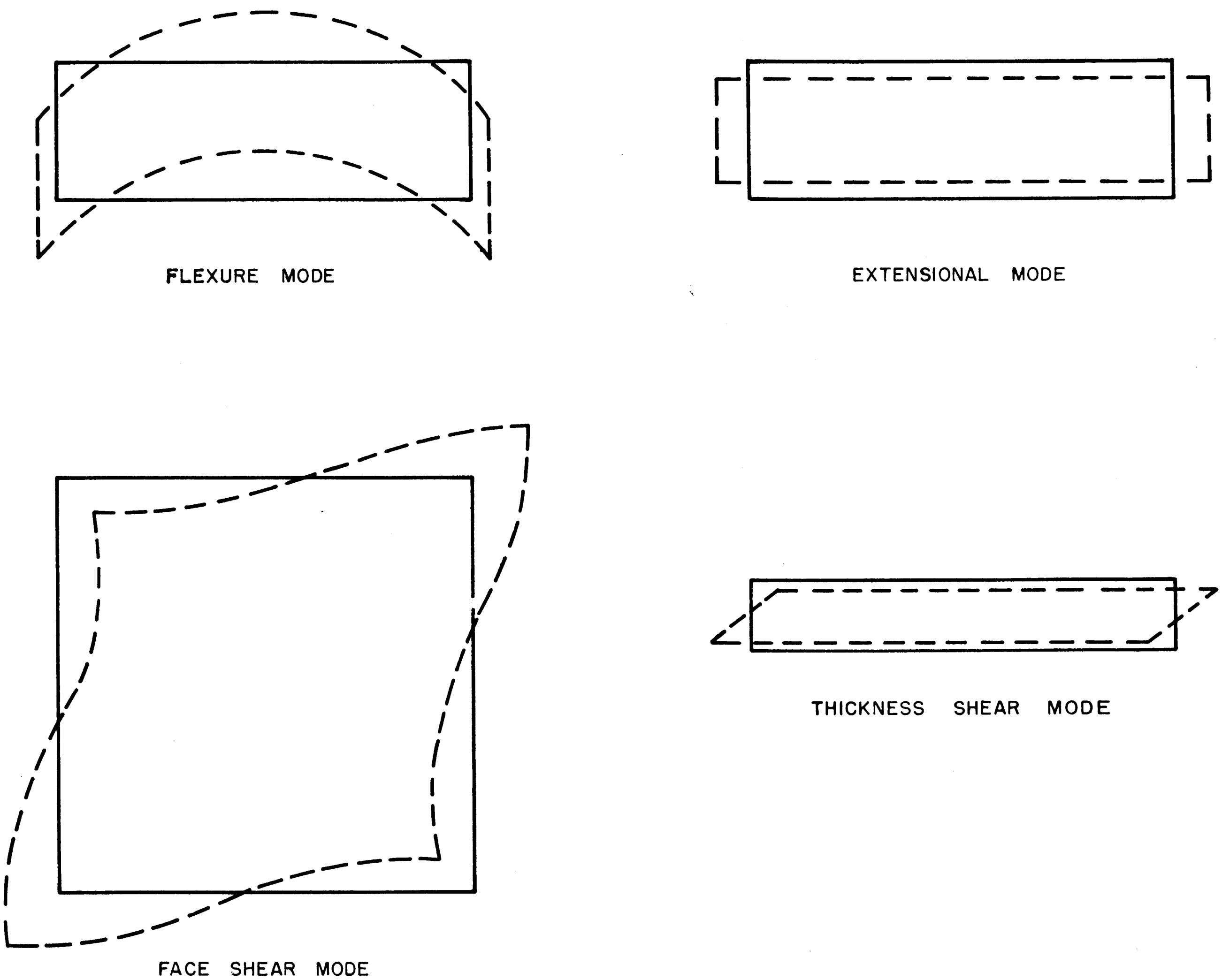

Figure 5-12. Modes of Vibration

or if the oscillators are operating on a nominal frequency of 1 mc, the difference is 1 part in 10^6. If the phase changes only 3.6 degrees in 10 seconds, the difference is only 1 part in 10^9. Thus, small differences in frequency can be measured and recorded. The resulting record will be an indication of the relative short-term stabilities of the oscillators.

4. QUARTZ RESONATOR THEORY

a. CONSTRUCTION AND OPERATION

Quartz resonators are electromechanical devices having extremely high Q's and stable resonant frequencies and are used as resonant circuits in electronic oscillators and filters. Quartz is a piezo electric material, that is, mechanical deformation of the quartz causes an electric charge to appear on certain faces, and conversely, application of voltage across the quartz causes a mechanical deformation. The quartz resonator unit generally consists of a crystalline quartz bar or plate provided with electrodes and suitably mounted in a sealed holder. The mounting structure supports the bar or plate at nodal points in its vibrational pattern so that damping of the mechanical vibrations with resultant degradation of Q is minimized. The bar or plate is cut from the mother crystal at a carefully controlled angle with respect to the crystallographic axes and finished to close dimensional tolerances. The quartz bar or plate has a mechanical resonant frequency determined by its dimensions. This resonant frequency changes with temperature, but by properly orienting the angle at which the blank is cut from the mother crystal, this temperature coefficient can be minimized. Commonly used orientations have been given designations, such as AT, CT, and DT cuts. Figure 5-11 illustrates the relationship between these cuts and the crystallographic axes. Proper orientation of electrodes on the quartz plate provides electric coupling to its mechanical resonance. The electrodes usually consist of a metal plating which is deposited directly on the surface of the quartz plate. Connections from these electrodes to external circuits are usually made through the mounting structure. After the blank has been cut from the mother crystal, it is reduced in thickness by successive stages of lapping until it is within etching range of the specified frequency. After thorough cleaning, the blank is etched to final frequency for pressure-mounting or to the preplating frequency if the electrodes are to be metal plated and the unit wire mounted. After the etching process, the blank is again thoroughly cleaned. After cleaning, the blank is base plated, recleaned, and wire mounted in a clean, moisture free, hermetically sealed holder designed to support the crystal unit against the effects of vibration. After mounting, the metal plated quartz plate is adjusted to the precise final frequency by additional plating. Typical metals used for plating are gold, silver, aluminum, and nickel. Silver is the metal most often used. Quartz crystal units vibrate in different modes depending upon the principal resonant frequency, the three most common modes being flexure, extensional, and shear. In high-frequency precision type units, the shear mode is used. Figure 5-12 illustrates the various modes of vibration.

b. CHARACTERISTICS

Two terminal plated quartz resonators may be represented by the electrical equivalent circuit shown in figure 5-13. The series arm consisting of R_1, L_1, and C_1 represents the motional impedance of the

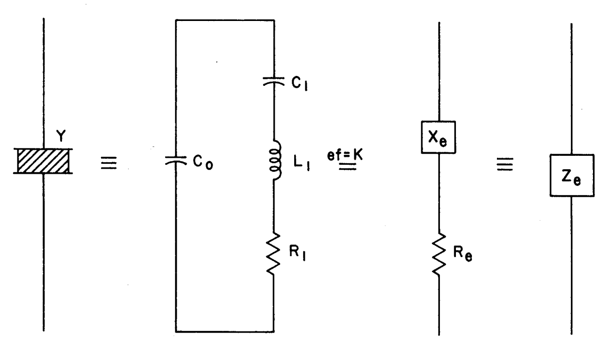

Figure 5-13. Quartz Resonator Equivalent Circuit

quartz plate while C_0 represents the electrode capacitance, C_2, plus the holder capacitance, C_h. At a single frequency this can be simplified to an effective reactance, X_e, in series with an effective resistance, R_e. These impedances are a function of frequency as shown in the impedance versus frequency curve illustrated in four views in figure 5-14. The frequency f_S

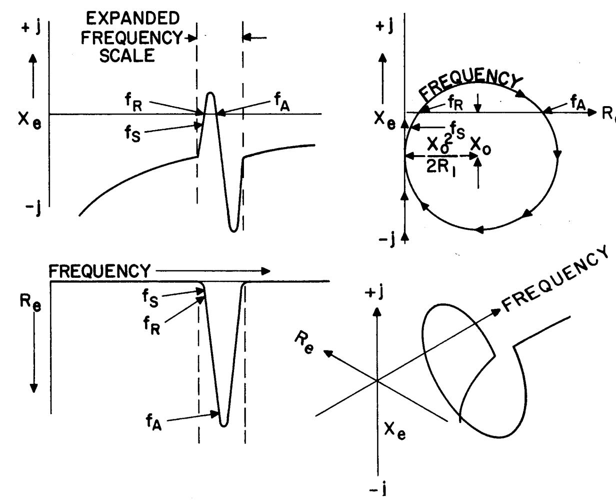

Figure 5-14. Impedance Versus Frequency Curve

is the resonant frequency of the series arm and f_R is the resonant frequency of the quartz resonator unit. The antiresonant frequency of the resonator, f_A, is only a fraction of one per cent higher than f_R. At frequencies removed from f_A by about one per cent, the resonator appears to be a capacitor having a value C_o. Resonators have a number of responses of lesser degree which are usually called unwanted responses. However, certain responses that are approximately harmonically related to the main response are called overtones and are used to control the frequency of vhf oscillators. The equivalent circuit values of a resonator can be controlled to about ±10% except for the series arm resistance, R_1. The resonant frequency can be controlled to close tolerances by close dimension control in the construction of the quartz plate. The resonator performance in a particular application can be calculated if the values of the equivalent circuit are given. If a capacitance C_x is added in series with the resonator and this combination operated at its series resonant frequency f_x, the following formulae hold.

$$X_e = \frac{1}{2\pi f_x C_x}$$

$$R_e = \frac{X_o}{2R_1} - \sqrt{\frac{X_o^4}{4R_1^2} - (X_o + X_x)^2} \quad \text{if } X_o^2 \gg R_1^2$$

$$R_e \approx \left(\frac{C_o + C_x}{C_x}\right)^2 R_1$$

$$R_1 \approx \left(\frac{C_x}{C_o + C_x}\right)^2 R_e$$

$$f_x \approx f_s \left[1 + \frac{C_1}{2(C_o + C_x)}\right]$$

$$\frac{df_x}{f_x} \approx - \frac{C_1}{2(C_o + C_x)^2} \, dC_x$$

The frequency range over which a quartz resonator operates best is determined by the type of cut. Each type of cut has its own optimum frequency range as determined by the physical dimensions of the resonator plate. The following table lists the different cuts and their normal frequency range.

TABLE 5-1

FREQUENCY RANGE OF QUARTZ RESONATORS

Cut	Normal Frequency Range
Fundamental AT	500 kc to 20 mc
3rd Overtone AT	10 mc to 60 mc
5th Overtone AT	30 mc to 80 mc
7th Overtone AT	60 mc to 120 mc
CT	300 kc to 800 kc
DT	200 kc to 500 kc
NT	16 kc to 100 kc
+5°X	90 kc to 300 kc
Bounded +5°X	1.2 kc to 10 kc

Temperature characteristics of quartz resonators are determined mainly by the orientation of the cut with respect to the crystallographic axes. The frequency versus temperature characteristics are shown in figure 5-15. The peaks of the parabolic shaped curves can be moved so as to appear at any desired temperature by changing the orientation of the cut slightly, and the S-shaped curve of the AT cut resonator can be tipped up or down by the same technique. It is seldom possible to adjust a quartz resonator to an exact resonant frequency at a specified temperature. Normal finishing tolerance for commercial units is about ±20 parts in 10^6. However, in precision resonators, finishing tolerances as low as 1 part in 10^6 have been achieved.

The resonant frequency of a resonator and the resistance of the series arm are, to some extent, a function of the amplitude of vibration or the power dissipated in the resonator. Below a current of about 100 microamperes, the frequency and resistance are essentially constant. As the current exceeds this critical value, the series arm resistance, R_1, increases; and the resonator frequency changes as the square of the current. In AT cut elements, the frequency increases about 0.1 part in 10^6 per milliwatt per mc. At still higher values of current, the frequency drifts considerably because of self-heating and

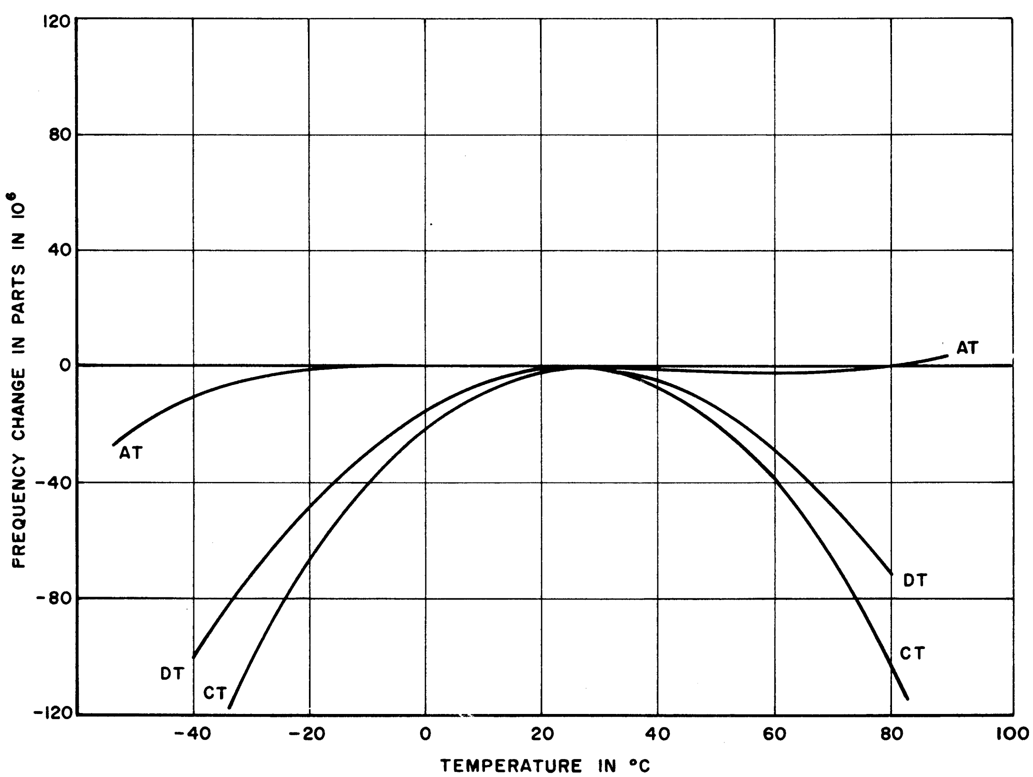

Figure 5-15. Frequency Versus Temperature Characteristics

finally the resonator fractures because of the large amplitude of vibration. Also, coupling of harmonically related modes of vibration can occur because the vibrations are not linear at the higher amplitudes. This coupling degrades the Q of the wanted response, and since these other modes usually have poor temperature coefficients, the Q depends upon both ambient temperature and resonator current. This Q degradation is known as an activity dip. In AT cuts, the unwanted responses within several per cent of the desired frequency are usually higher in frequency than the desired response. These can become prominent enough to control the frequency in oscillator applications. The resonator frequency also changes some with time due to surface contamination of the quartz and to sublimation of the plated electrodes. The actual amount of change depends on the cut, design, cleanness, and construction of the resonator unit. The rate of aging generally increases rapidly with temperature and is sometimes 100 times greater at 40°C than at 0°C. Therefore, aging is more rapid in oven controlled units. At present, the aging in commercial high-frequency AT cut crystal units is about 40 parts in 10^6 per year at 85°C. However, in precision, oven controlled resonators aging rates as low as 1 part in 10^9 per month have been achieved. Normal aging rates for precision units are 1 part in 10^8 per day. Recent studies on the aging rate of quartz resonators indicate that their stability is improved by very low temperature operation. Figure 5-15.1 shows that stability on the order of 1 part in 10^{10} per day can be achieved by operating commercial grade crystals at 4°K.

c. CONSTRUCTION OF PRECISION RESONATORS

Figure 5-16 shows the construction and mode of vibration of a precision crystal resonator, 5th overtone AT cut. The blank is made circular with one spherical surface and one flat surface. In a crystal of this shape, all of the mechanical vibration takes place near the center of the plate and the edges remain dormant. Thus, supports can be attached to the edges of the plate without degrading Q through damping of the vibrations. The quartz plate is usually given a high polish

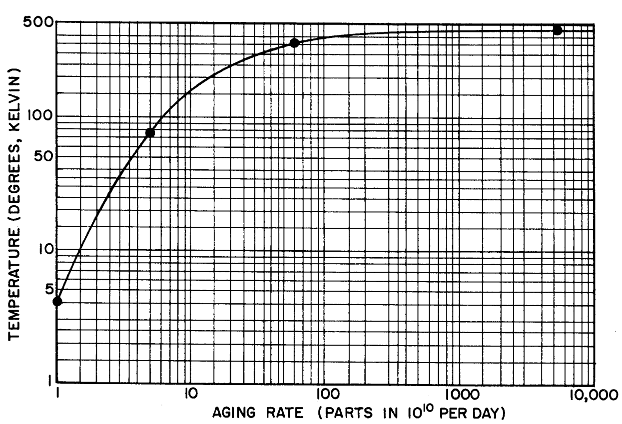

Figure 5-15.1. Quartz Resonators, Aging Rate versus Temperature

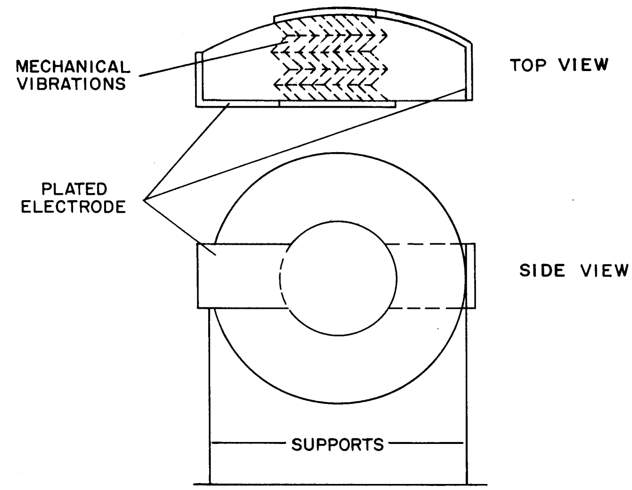

Figure 5-16. Precision Quartz Resonator, Construction and Mode of Vibration of 5th Overtone AT Cut

which may be followed by a brief etching operation before the electrodes are plated on. The plating operation is performed in a vacuum in order to minimize contamination and after plating, the unit is sealed in an evacuated glass or metal envelope. The mode of vibration used is the 5th overtone in thickness shear. Use of this mode of vibration greatly decreases the volume to effective surface ratio and at the same time reduces the effective surface area exposed to contamination since ten effective surfaces, consisting of the five interfaces resulting from 5th mode operation, are inside the crystal. Typical applications for these units are in 2.5 mc and 5 mc frequency standards. The resonant frequency of 5th overtone AT cut crystals is not affected by shock and vibration below the level that permanently damages the mounting structure.

5. OSCILLATOR THEORY

a. GENERAL THEORY

Oscillator operation can be analyzed on a feedback basis wherein the oscillator consists of an amplifier with a frequency selective device which couples energy at the desired frequency from the output back to the input. When the circuit is adjusted so that the amplifier supplies energy at the desired frequency sufficient to overcome the losses in the feedback path, the circuit oscillates and generates a signal at a frequency controlled by the resonant frequency of the feedback path. If energy is to be coupled out of the oscillator and used to drive other devices, the amplifier must supply this energy in addition to that required to overcome the losses in the feedback path.

In crystal-controlled oscillators a quartz resonator network provides the coupling from the output of the amplifier to its input. Because of its high Q, the resonator operates as a highly selective feedback network with extremely high attenuation of frequencies on either side of its resonant frequency. Thus the frequency of oscillation cannot deviate appreciably from the resonator frequency. Since the output of the feedback network is the input of the amplifier, the total phase shift around the loop must be zero. For this reason the resonator must compensate for phase shifts in the rest of the oscillator circuit and these phase shifts will affect the frequency stability of the circuit.

Another method of analysis is that based on the negative resistance theory. Figure 5-17a is an

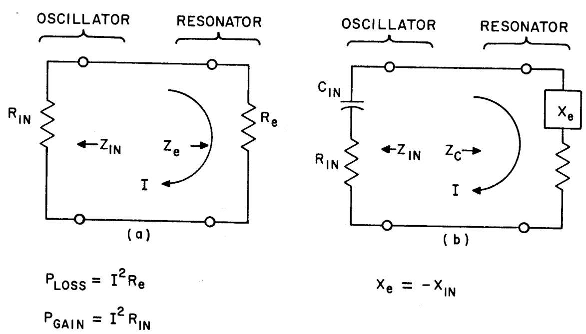

Figure 5-17. Equivalent Circuit of a Crystal-Controlled Oscillator

equivalent circuit of an oscillator operating at series resonance. The input impedance of the oscillator is a negative resistance, R_{in}, and the resonator has an effective resistance, R_e. The power loss in the resonator is I^2R_e, and the power supplied by the oscillator is I^2R_{in}. If the power gain is greater than the power loss, oscillations will build up; and if the power gain is less than the power loss, oscillations will die out. The negative oscillator input resistance is a function of the current I so that R_{in} will decrease as oscillations build up, until R_{in} equals R_e and a stable amplitude is reached. A more general case is illustrated in figure 5-17b in which the oscillator input impedance has a capacitive component. It is standard practice to make this input capacitance, C_{in}, 32 uuf at frequencies above 500 kc and 20 uuf at frequencies below 500 kc. The entire network oscillates at a frequency such that $X_e = -X_{in}$, and the equations for power loss and gain given for figure 5-17a still apply. All types of oscillators can be analyzed in this manner except that in a few special cases the reactive component of oscillator input impedance may be inductive.

Mathematical analysis consists of replacing the resonator with an imaginary test voltage generator and solving for $Z_{in} = \frac{E_{in}}{I_{in}} = R_{in} + jX_{in}$. Figure 5-18 illustrates a method of calculating the power dissipation in

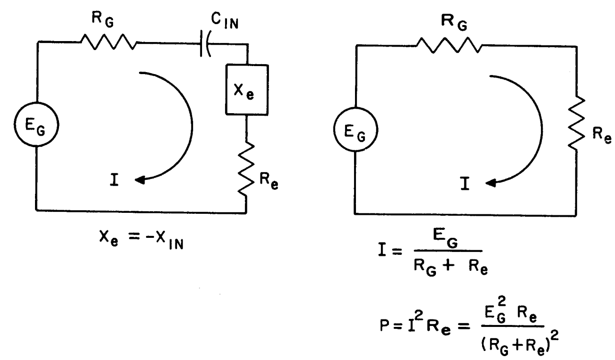

Figure 5-18. Calculation of Resonator Power Dissipation

the resonator for vacuum-tube saturation limiting. In the first equivalent circuit the oscillator is represented by a generator, E_G, with a series generator resistance, R_G. Since the resonator reactance, X_e, equals the negative reactance, $-X_{in}$, of the input capacitance, C_{in}, these two reactances cancel, and the equivalent circuit is reduced to the second circuit shown in figure 5-18. After the grid voltage on the oscillator tube reaches the value that saturates the tube, the generator voltage E_G remains relatively constant and independent of grid drive. Then resonator current is given by $I = \frac{E_G}{R_G + R_e}$, and the power dissipated in the resonator is given by $P = I^2R_e = \frac{E_G^2 R_e}{(R_G + R_e)^2}$.

b. TYPICAL OSCILLATOR CIRCUITS

Quartz crystal resonators have two resonant frequencies. At one frequency they exhibit antiresonant characteristics, and at a slightly lower frequency they exhibit series resonant characteristics. At frequencies between these two the resonator reactance is inductive, and at frequencies outside this range the reactance is capacitive. The design of the oscillator circuit determines in which part of the reactance characteristic it will be used. In the oscillator represented by figure 5-19, the series resonant response is used. The amplifier is designed so that the total phase shift from amplifier input to output is zero. Since the total phase shift around the complete loop, including the feedback network, must be zero, the feedback network must also have zero phase shift. If the feedback network is to have zero phase shift, it

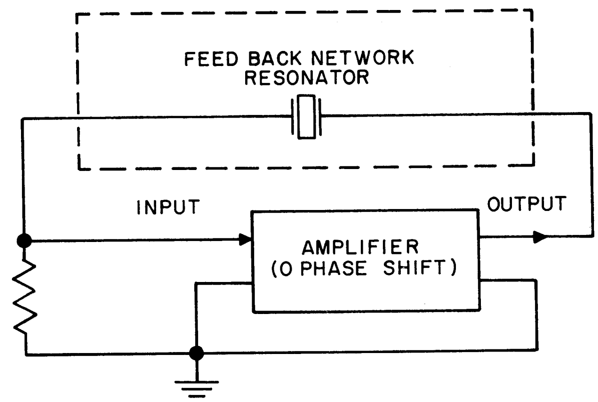

Figure 5-19. Basic Crystal Oscillator Operating the Resonator at Series Resonance

must be resistive at the frequency of oscillation. The quartz resonator which forms the feedback network is resistive at two frequencies, its antiresonant frequency and its series resonant frequency. Since the resonator is in series with the feedback path, the frequency at which it offers the least resistance to the signal is its series resonant frequency, and this will be the frequency of oscillation.

Figure 5-20 shows the basic Pierce oscillator circuit, an equivalent circuit, and a vector diagram showing the phase relationships, neglecting circuit losses. In this oscillator the feedback network operates at antiresonance, but the resonator operates at a point between its series resonant frequency and its antiresonant frequency where it is sufficiently inductive to resonate with C_p and C_g in series. The generator voltage $-uE_g$ is the grid voltage multiplied by the gain of the tube. Since the circuit representing

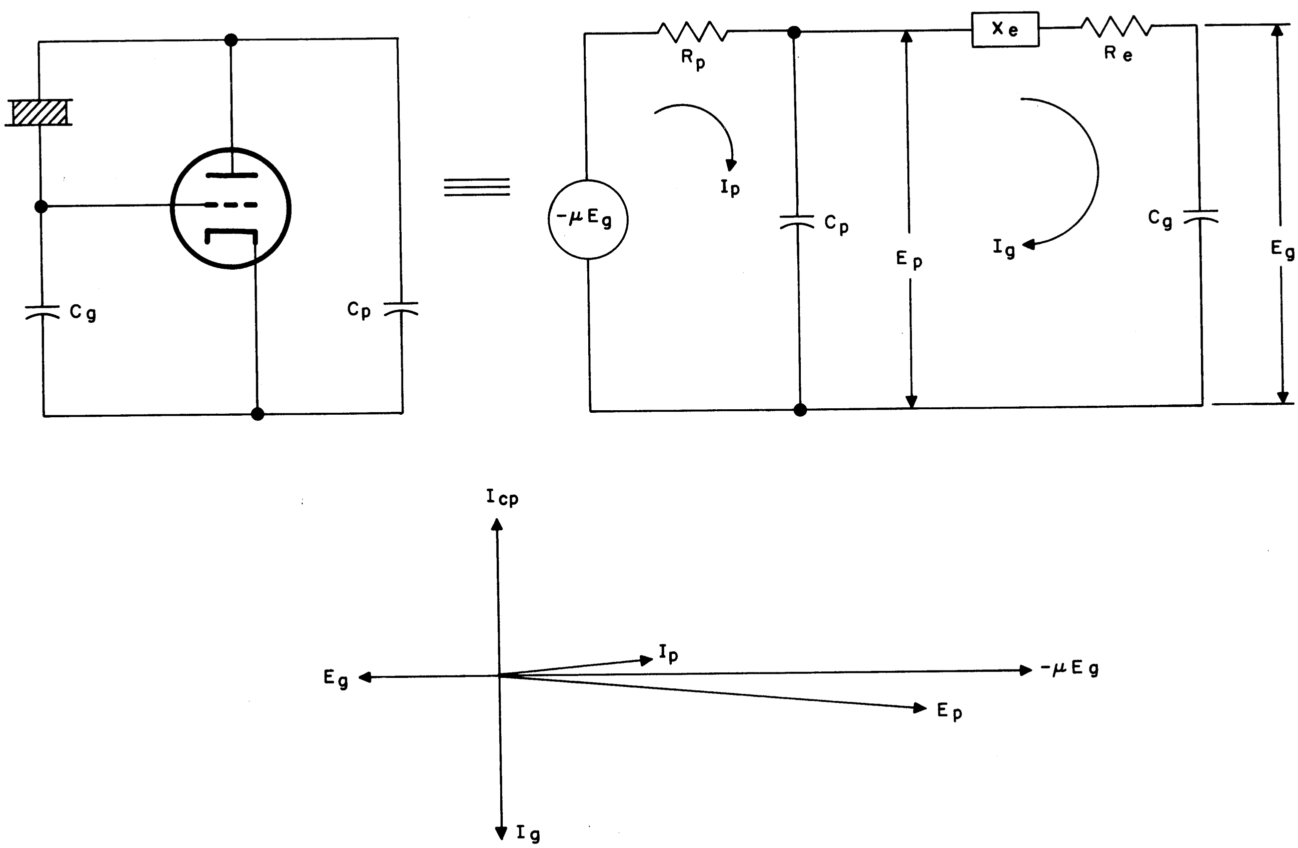

Figure 5-20. Basic Pierce Oscillator

the generator load is resonant, I_p will be in phase with $-uE_g$; and since the branch consisting of X_e, R_e, and C_g is inductive, I_g will lag $-uE_g$ by 90°. The voltage, E_g, developed across C_g will lag I_g by 90°. Therefore, E_g will lag $-uE_g$ by 180°, and since the tube introduces another 180° phase shift, the condition that there be zero phase shift around the loop is satisfied.

c. PRECISION CRYSTAL-CONTROLLED OSCILLATORS

In the design of precision oscillators, several precautions must be taken to minimize instabilities. The construction of the quartz resonator itself was described in paragraph 4 of this chapter. Additional precautions to be observed in the use of quartz resonators in precision oscillators are listed below.

(1) The components that make up the resonant circuit must be placed in a controlled environment.

(2) The amplitude of oscillation must be controlled to avoid instabilities caused by nonlinearity in the vibration pattern of the resonator at high amplitudes.

(3) Phase instabilities in the active amplifying portion of the oscillator must be held to a minimum.

(4) External circuitry must be isolated from the oscillator so that reactive components are not reflected back into the resonant circuit to cause instability.

(5) The Q of the resonator should be high so that loop phase shifts can be compensated for with minimum change in resonator operating frequency. In addition, high Q makes possible low coupling between the resonator and the active amplifying portion of the oscillator, thus minimizing the effect of the active network on the resonator.

(6) Nonlinearities in the active amplifying portion of the oscillator cause harmonic distortion. Adjacent harmonics are mixed together in the same or other nonlinear portion of the circuit after having passed around the feedback network. The fundamental frequency component thus produced is usually not phase stable and causes phase instability in the oscillator. Therefore, the amplifier must be operated on the linear portion of its characteristic.

Figure 5-21 illustrates the principle of operation of the Meacham oscillator. The resonator, Y1, operates at its series resonant frequency and thus offers a low resistance and zero phase shift to the frequency of oscillation. The opposite leg of the bridge circuit is an incandescent lamp which when cold also has a low resistance. Resistors R1 and R2 have about the same resistance as the effective resistance of the resonator at its series resonant frequency. This condition exists when oscillations start. The coupling between the amplifier and the feedback loop is relatively tight, and there is a large amount of positive feedback. As oscillations build up, the

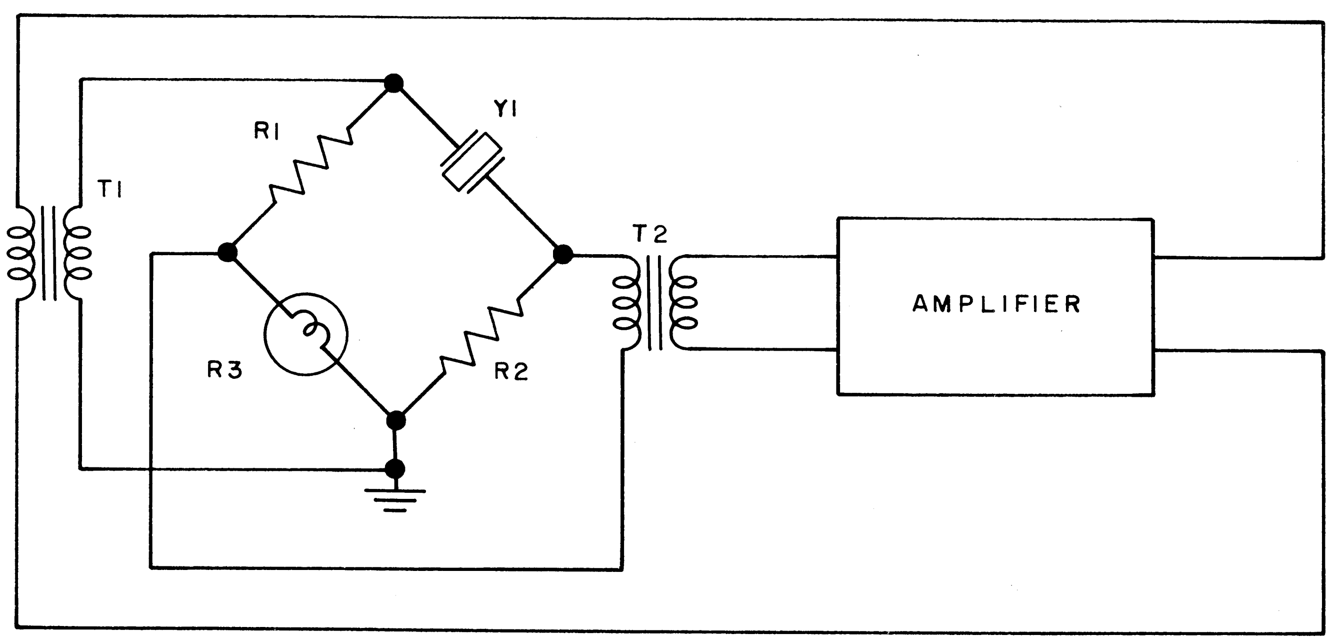

Figure 5-21. Meacham Oscillator

lamp, R3, is heated by the r-f current, and its resistance increases until it is almost equal to that of R1. As the lamp resistance increases, the bridge approaches balance; the positive feedback is reduced until the bridge is almost in balance, and the residual positive feedback is just sufficient to sustain oscillation. This oscillation is usually used only at frequencies below 1 mc because of the difficulties of obtaining transformers that do not cause phase instabilities at the higher frequencies.

Figure 5-22 is a schematic diagram of a typical Pierce oscillator used in high precision frequency standards. The 1 mc quartz resonator, V1, is a fundamental AT cut crystal, sealed in an evacuated glass envelope. Its temperature coefficient is only several parts in 10^7 per degree centigrade. The components that make up the resonant circuit, Y1, R1, C1, C2, and C3 are housed in an oven in which the temperature is held constant to better than .01°C. Capacitor C1 and resistor R1 hold the d-c voltage impressed on the resonator, Y1, to a minimum. The resonator has a minimum Q of 1 million, thus capacitors C2 and C3 can be made large to bypass effectively the plate and grid of the tube to ground and reduce the coupling between the resonator and the active portion of the circuit to a low value. In addition, all frequency controlling components are isolated from other circuit elements by shielding. Capacitor C4 is a precision variable capacitor which provides a small range of adjustment of the resonant frequency of the circuit. The total range of adjustment is about 4 cps at the nominal operating frequency of 1 mc. The output of the oscillator is coupled to an untuned buffer stage which isolates the oscillator from succeeding stages. Two stages of amplification follow the buffer stage and provide additional isolation. The amplitude of oscillation is controlled by negative voltage developed in the grid circuit of the last amplifier stage. Cathode bias on this tube delays development of negative voltage until the signal applied to the grid reaches a predetermined level. When this level is reached, the resultant negative voltage couples to the grid of the oscillator tube through an RC filter increasing grid bias, and thus reducing the tube gain, and limiting the amplitude of oscillation to a low level. This automatic amplitude control system holds the operating power level in the quartz resonator to less than .1 microwatt. This type of oscillator has attained short-term stability of better than 1 part in 10^{10} and long-term stability of better than 1 part in 10^9 per day. Oscillators are now being designed to use the 5th overtone AT cut crystal. These are expected to have even better stabilities than oscillators using the fundamental AT cut crystal.

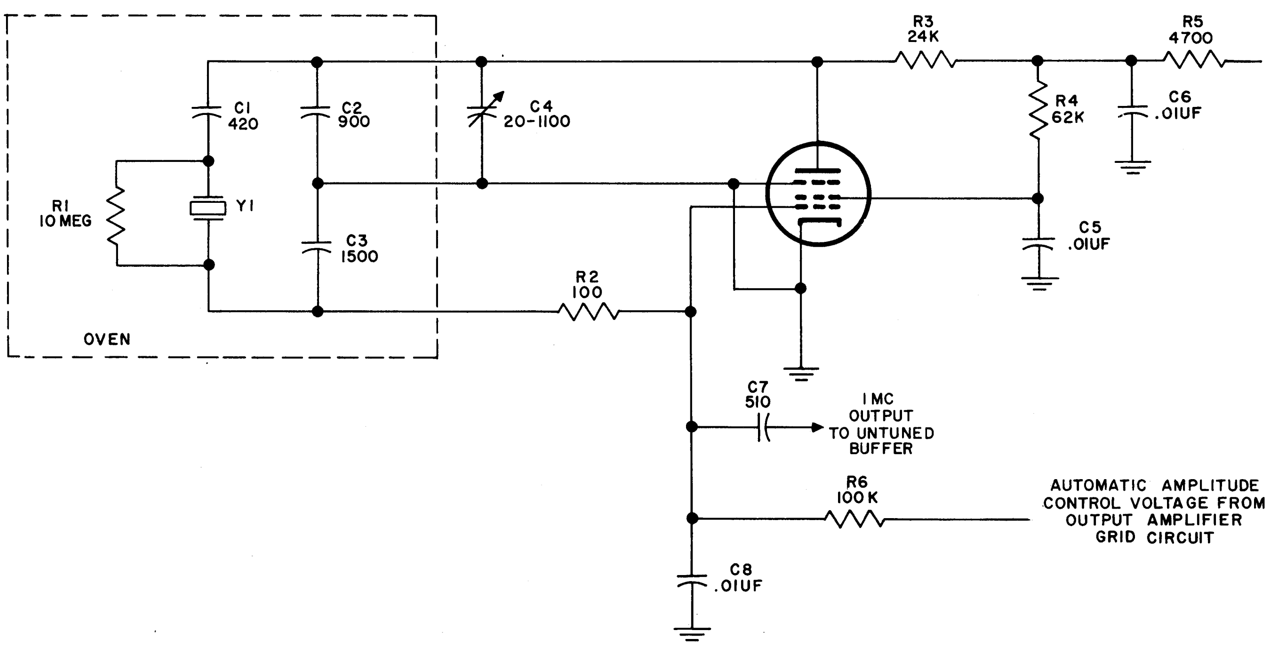

Figure 5-22. Precision Pierce Oscillator

6. OVEN THEORY

a. GENERAL THEORY

Since all quartz resonators have some variation of frequency with temperature, the resonator must be kept at a constant temperature in order to achieve maximum stability. In most frequency standards, this is accomplished by placing the resonator in an oven and then maintaining the oven temperature at a level somewhat higher than the ambient temperature surrounding it. The six items listed below make up a typical oven.

(1) The resonator or device to be temperature controlled

(2) The oven heater

(3) A device for controlling the power delivered to the heater

(4) A temperature sensing element

(5) A heat sink (ambient temperature around oven)

(6) Thermal insulation or thermal resistance

The operation of the oven can be compared to the operation of an electrical bridge circuit as illustrated in figure 5-23. The arms of the bridge R1, R2, R3,

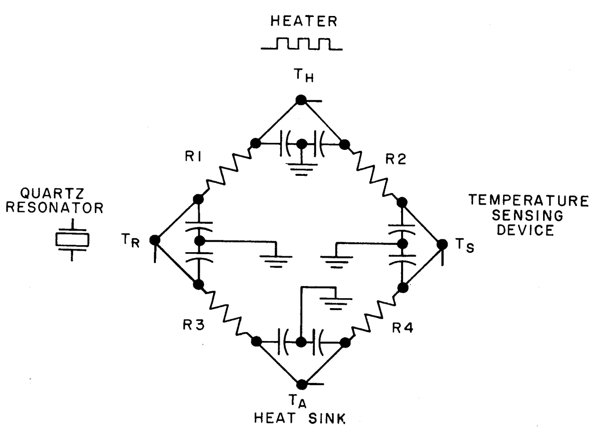

Figure 5-23. Oven Operation Equivalent Electrical Circuit

and R4 represent thermal resistance, that is, resistance to heat flow. The temperatures T_H, T_R, T_A, and T_S are analogous to electrical potentials at the points indicated. T_H is the heater temperature; T_R is the resonator temperature; T_A is the temperature surrounding the oven, and T_S is the temperature of the sensing element. The heat storage or thermal capacities of the materials in the heat flow path are analogous to electrical capacitance. The temperature of the heater T_H, is regulated by the sensing element through a servo system so that the temperature T_S remains constant. To maintain the temperature T_R of the resonator constant regardless of variations in T_A, T_R must equal T_S, that is, the bridge must be balanced or R1/R3 must equal R2/R4. Conditions for balance are less critical if R1 and R2 are made very small as compared to R3 and R4, since then T_H, T_S, and T_R will be more nearly equal. The time lag between T_H and T_S, caused by the time constant of the thermal resistance R2 and its associated thermal capacities, causes the servo system to hunt and this in turn causes the temperature T_S to cycle. Reducing the time constant of R2 and its associated capacities to a very low value eliminates this cause of hunting. However, another cause of hunting is the operating differential of thermostats. When these are used as temperature sensing devices, the time constant of R1 and its associated capacities must be made long in order to filter out variations in T_R caused by hunting in the servo system. If proportional control is used, the time lag due to operating differential in the sensing element is eliminated, and the time constant of R2 and its associated capacities can be made very low to eliminate hunting. If the servo system is free of hunting, then the time constant of R1 and its associated capacities can be made low, and if at the same time the time constants in the R3 leg and the R4 leg are made long, T_S and T_R will be on an isothermal line with T_H. Ovens using this system can maintain temperature within .01°C.

b. TYPICAL PRECISION OVEN

Figure 5-24 illustrates the construction of a typical precision oven. In this oven, the resonator, the heater, and the temperature sensing element are all in an isothermal space. The resonator in its sealed envelope is housed in an aluminum cylinder upon which the heater is wound. Because of the high heat conductivity of aluminum and because the resonator is almost completely surrounded by aluminum, the temperature of the resonator is nearly identical to that of the aluminum enclosure. The heater is wound on this enclosure and tightly coupled to it thermally. Thus the resistance R1 in figure 5-23 and the thermal time constant between T_H and T_R are nearly zero. The heater is constructed so that it is also the temperature sensing element, making R2 in figure 5-23 and the time constant between T_H and T_S nearly zero. The resistances R3 and R4 are made very large by housing this assembly in a vacuum bottle. The vacuum bottle is enclosed in a second aluminum cylinder which makes T_A uniform on all sides of the oven.

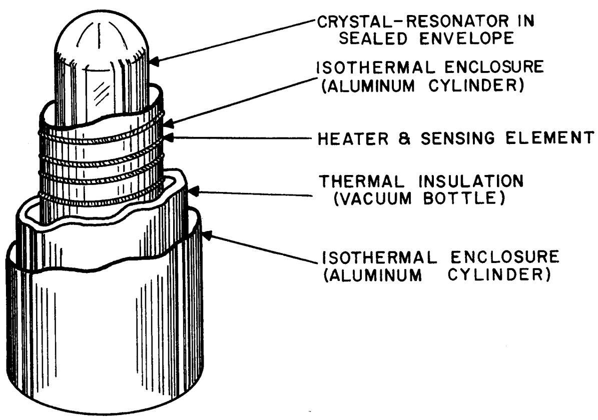

Figure 5-24. Typical Oven Construction

Since the heater, the resonator, and the temperature sensing element have been placed in an isothermal space well isolated from the ambient temperature, the only remaining requirement is to maintain the heater at a constant temperature. The circuit of figure 5-25 satisfies this requirement. The bridge circuit, HR601, performs two functions. It is the heating element for the oven and the control element for the oven oscillator. Two arms of the bridge are made of nickel wire, and the other two arms are made of Low Ohm wire. The arms are of selected lengths so that their resistances at the desired oven temperature are almost equal. When the oven temperature is low, the nickel wire has less resistance than the Low Ohm wire, and terminals 5 and 7 of the secondary winding of T601 see less resistance to ground than do terminals 4 and 6. At the same time, terminals 4 and 6 of T601 see less resistance to the feedback path than do terminals 5 and 7. As a result, the alternating current flowing through the bridge is applied as positive feedback to the first amplifier stage. Under these conditions, the circuit oscillates at an amplitude determined by the amount of bridge unbalance which in turn is controlled by the temperature Thus, proportional control is provided, and the thermal lag inherent in thermostatic devices is eliminated. The power supplied to HR601 by the oscillator heats the oven; and as the temperature approaches the desired level, the bridge approaches balance reducing the amount of feedback until at the desired temperature, it is just sufficient to sustain oscillation. When the oven reaches this steady state condition, the oven control osciliator supplies just enough power to the heater to replace the heat lost to the surrounding medium and maintains the oven temperature constant within .01°C. If for any reason the temperature of the oven rises above the desired level, the bridge becomes unbalanced in the opposite direction and resultant negative feedback prevents oscillation.

7. FREQUENCY DIVIDER THEORY

In order to obtain maximum stabilities, standard signals must be generated at higher frequencies than the lowest frequency required for use in the equipment. In order to obtain the lower frequencies, frequency dividers must be used, and if the divided frequency is to have the same stability as the original, these dividers must be under control of the standard. Figure 5-26 is a block diagram of a typical divider. The equipment contains two regenerative dividers which divide their input frequencies by 10. With a 1 mc input, this circuit provides outputs at 1 mc, 100 kc, and 10 kc. The principles of operation of the two dividers are identical except for the frequencies involved; therefore, only the 1 mc to 100 kc divider will be discussed. When the 1 mc signal supplied to

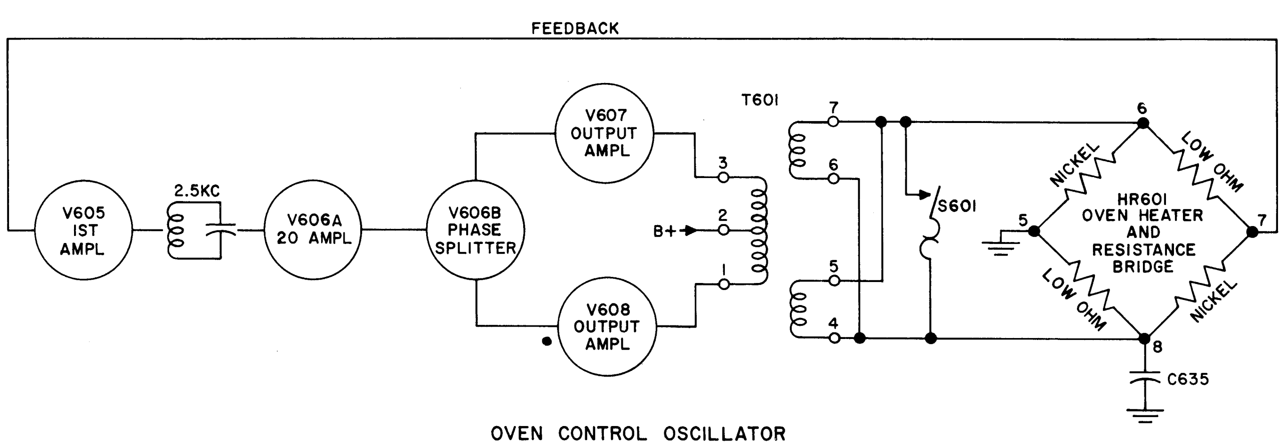

Figure 5-25. Oven Control Oscillator

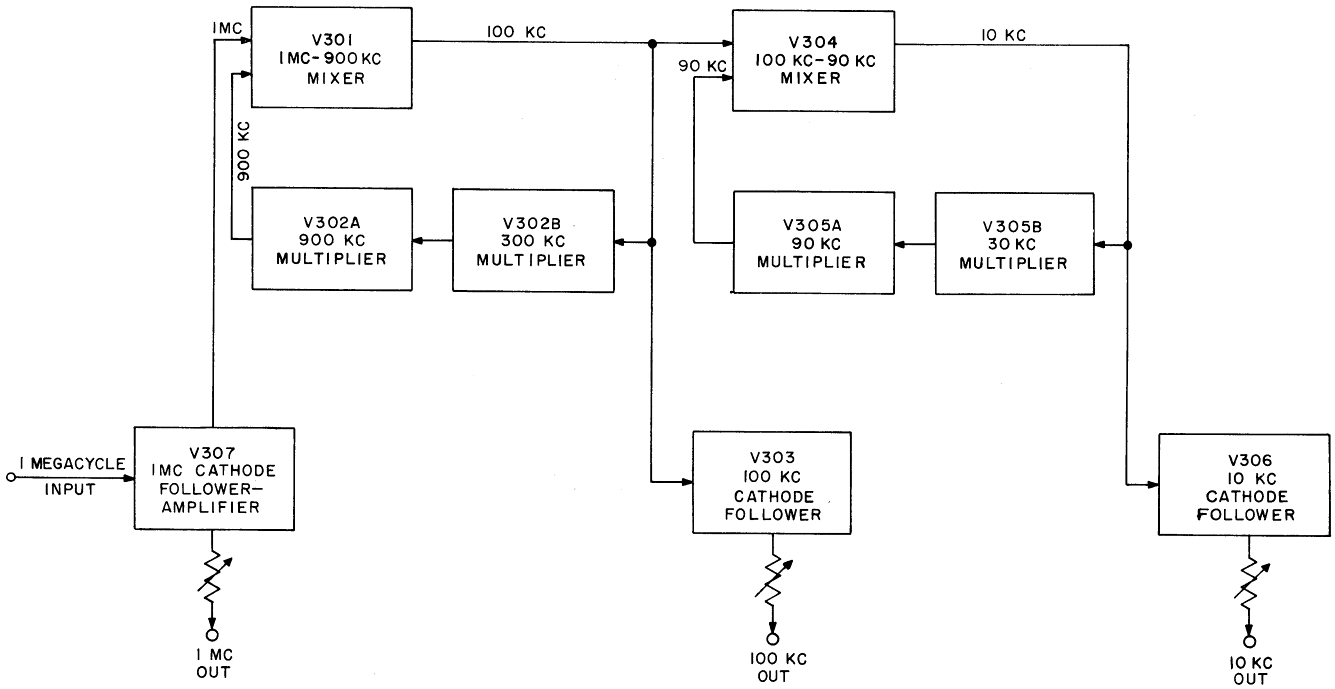

Figure 5-26. 8U-1 Frequency Divider, Block Diagram

the injection grid of mixer V301 is large enough to make the circuit sufficiently regenerative, noise energy at 900 kc appearing at the signal grid of V301 mixes with the 1 mc signal to produce sufficient 100 kc signal to drive multiplier V302B. This circuit multiplies the 100 kc signal by 3 producing a 300 kc signal which drives a second multiplier V302A. The 300 kc signal is again multiplied by 3 to produce a 900 kc signal for mixing in V301. The 100 kc signal thus produced is under complete control of the 1 mc signal. If the 1 mc injection falls below the threshold level, the loop gain of the circuit falls below the level required to maintain operation, and no output is available. The second divider circuit operates from the 100 kc signal in the same way to produce a 10 kc signal. The cathode followers used to couple the signals to external circuits provide isolation.

8. SYSTEM CONSIDERATIONS

In single-sideband communications, the total frequency shift in the system, both transmitting and receiving, should not exceed 50 cps. At 20 mc this requires a system stability of 2.5 parts in 10^6, including errors introduced by the propagating medium, Doppler shifts, and errors in terminal equipment. To assure total system stability of 2.5 parts in 10^6 over a period of months without readjustment, stabilities of 1 part in 10^8 per day are required in the frequency standards. Frequency, time, and phase stability requirements in other systems, such as Kineplex*, are even more severe. In the Kineplex system, 22 millisecond pulses are transmitted. Each pulse is a reference for the succeeding pulse. Short-term phase stability for this system must be within a few degrees over a 44 millisecond period. Frequency accuracy must be ±.5 cps to prevent deterioration of the signal. Errors of ±1 cps cause noticeable distortion and ±3 cps is the practical limit of permissible frequency error. Time accuracy within ±1 millisecond would provide a signal with no noticeable deterioration, but ±5 milliseconds is the practical limit of time error. Thus, in these systems, total system frequency stabilities of 6 parts in 10^7 and total system time stabilities of 1 part in 10^8 are required. In mobile systems, Doppler shifts, and time variations due to changing transmission path lengths must be compensated for either by automatic correction circuits or by manual readjustment of local equipment.

* Registered in U. S. Patent Office

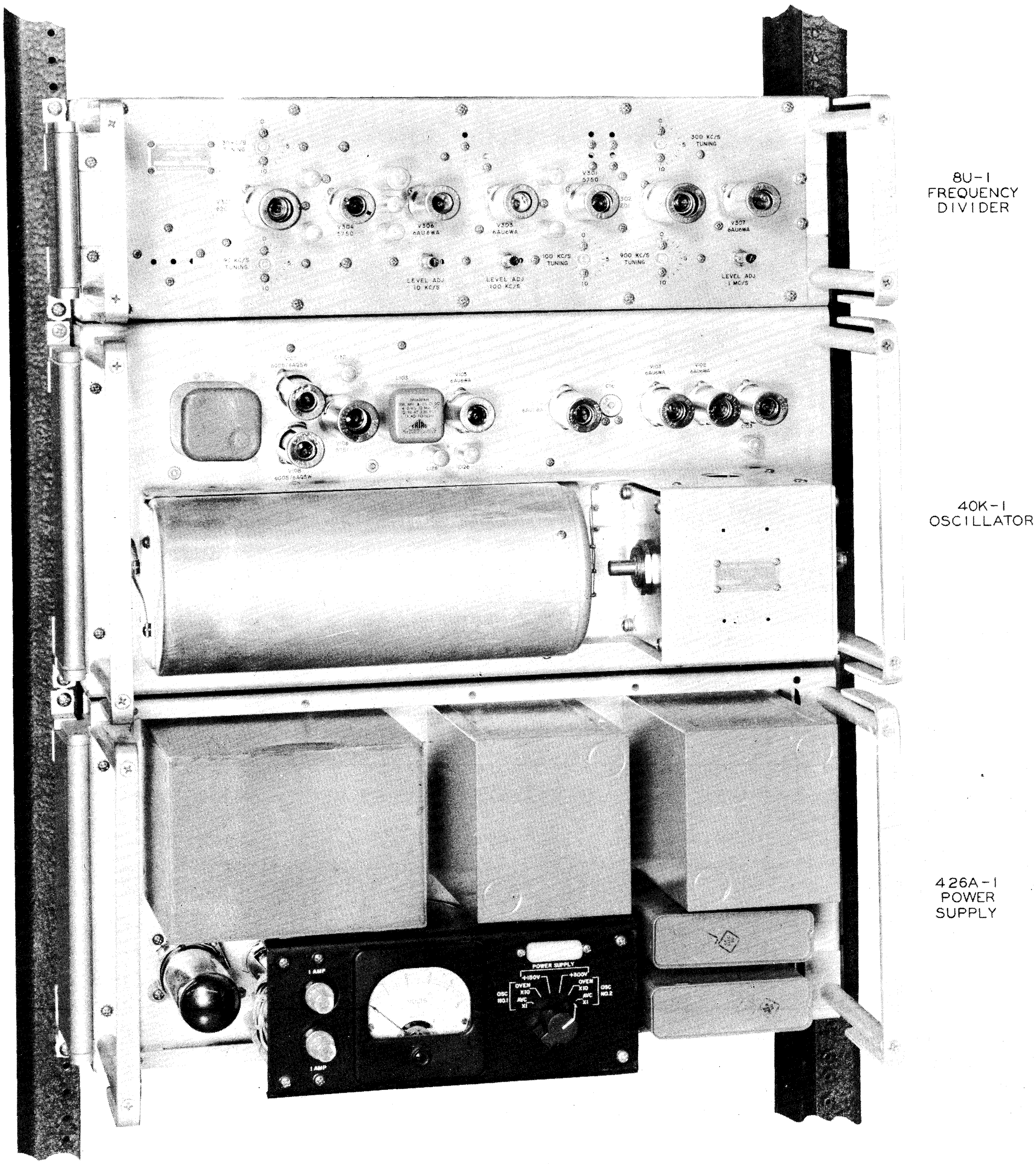

Figure 5-27. Typical Secondary Frequency Standard, Covers Removed

Figure 5-28. Collins Radio Company Primary Frequency Standard

CHAPTER 6
PRINCIPLES OF SERVOMECHANISMS

1. DEFINITIONS

A servomechanism is most commonly defined as a feedback control system of which at least one element is mechanical in nature. Voltage regulators for power supplies, automatic volume control and automatic frequency control circuits used in radio equipment and thermostats used to regulate temperature in home heating equipment and in various electrical appliances are examples of feedback control systems. Power steering, gun turret positioning devices, and airplane autopilots are examples of servomechanisms.

In all feedback control systems, the quantity to be controlled is measured in some manner. This measured value is compared to a desired, or reference, value to form an error signal, and the controlling action is governed by some function of the error signal. Feedback control devices may contain electrical, mechanical, pneumatic, hydraulic, and other types of elements. Frequently, a human operator is included in the feedback loop.

2. A TYPICAL POSITION SERVO SYSTEM

Figure 6-1 illustrates a typical position follow-up type of servomechanism. This type of device can be used for repeating the position of a shaft at a remote point. For example, in an airborne radio transmitter, it could make the shaft of a precision oscillator follow a dial in the pilot's control box. Follow-up servos are also used to repeat the shaft position of a delicate instrument at a shaft where a large amount of torque is needed. In this case, the purpose of the servo is to provide torque amplification.

In figure 6-1 the reference input R is a shaft position. A voltage proportional to the shaft position is obtained from a linear potentiometer connected across a battery. This voltage is mixed with a voltage proportional to the controlled variable to form the error signal E which is then amplified and applied to the winding of a motor. The motor shaft is coupled through a gear train to the load, which in most cases is a friction device, although it sometimes contains a

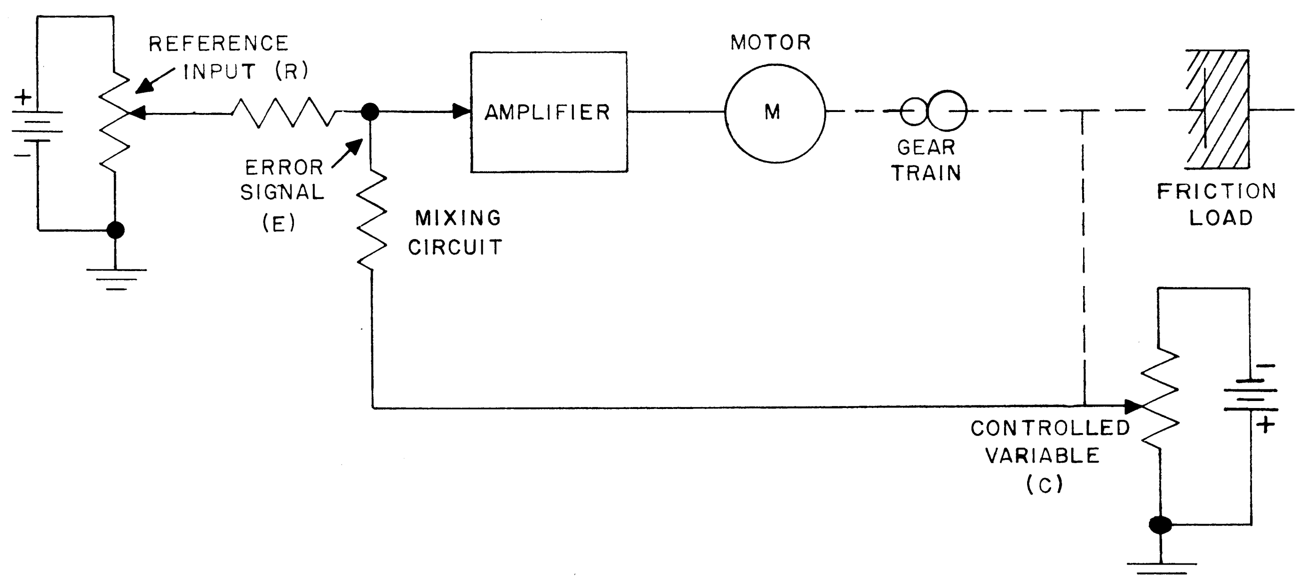

Figure 6-1. Position Follow-up Servomechanism