SECTION 2

ADVANCED
PRACTICAL
RADIO ENGINEERING

TECHNICAL ASSIGNMENT

CRYSTAL CONTROL
OF
RADIO FREQUENCIES

Washington, D. C.

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CRYSTAL CONTROL OF RADIO FREQUENCIES

FOREWORD

With the advent of standard broadcasting in the 1920's, the problem of frequency control of the transmitters came to a head. The ordinary vacuum tube oscillator depends for its frequency stability upon its tuned electrical circuits, and these are variable in their electrical characteristics, depending upon such factors as temperature and humidity.

Another factor affecting the stability is the Q of the tuned circuit; i.e., the ratio of its reactive to dissipative power. If the Q is high, then any tendency of the oscillator to change its frequency immediately brings strong corrective forces into play that prevent such variation. The basic problem is therefore to find a stable, high-Q circuit.

The solution is the quartz crystal. This natural substance, found mainly in Brazil, is of unsurpassed uniformity in structure owing to the unvarying manner in which the molecular forces act to produce the crystal. Its chemical stability is so great that it is unaffected by the elements, although it is normally enclosed in a holder to keep out dust, etc.

As a result, it has almost negligible damping when caused to vibrate mechanically. This is a property possessed to a high degree by most mechanical tuned configurations, in contradistinction to electrically tuned circuits, but is present to a preeminent degree in quartz. Hence a wafer of this crystal exhibits an extremely high Q, and is therefore particularly suited for frequency control.

However, a high mechanical Q is not sufficient. The device must also exhibit a corresponding electrical characteristic, in order to carry over its high mechanical Q into the oscillator circuit. This is brought about by the piezoelectric effect, according to which a mechanical deformation produces corresponding electrical charges on the crystal faces, and conversely, the introduction of electrical charges produces mechanical deformations.

As a result, a crystal can be employed as a tuned electrical element of extraordinarily high Q in an oscillator circuit, and with the proper precautions can hold the frequency of the oscillator constant to within 20 parts in a million. Indeed, under suitable conditions, the frequency can be kept so constant, that a synchronous motor clock, driven from such a source, has been constructed that is far superior to the most accurate mechanical chronometer ever built by man!

Today the crystal-controlled oscillator holds undisputed sway in broadcast practice, and accounts for the large number of broadcast stations that are permitted to operate simultaneously. It is therefore evident that this technical assignment covers a very important phase of radio engineering, and is therefore a very important text.

Upon completing its study, you will not only have an excellent knowledge of how the crystal is prepared, its properties, and the variations in cut, but you will also obtain a comprehensive insight as to how it is employed in actual practice for frequency control and frequency measurement. I therefore recommend that you give this assignment your undivided attention.

E. H. Rietzke,
President.

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CRYSTAL CONTROL OF RADIO FREQUENCIES

CRYSTAL CONTROL OF RADIO FREQUENCIES

INTRODUCTION.—For many years, it has been the goal of engineers to produce alternating current energy at a constant frequency. Many and ingenious are the schemes which have been and are employed to reduce the frequency error or deviation but no complete solution has appeared. However, excellent results have been obtained in the production of almost constant frequency. One of the mechanical-electrical schemes which has been used for the production of almost constant frequency is the use of a precision temperature-controlled low-frequency tuning fork to produce the fundamental frequency and then, by the use of frequency multipliers, to produce any desired harmonic of the fundamental output frequency. This method is open to the objection that a large number of frequency multipliers are required. For example, to multiply the frequency of a 500 cycle fork to one of the lowest frequencies in the broadcast band, say 550 kc/s, would require frequency multiplication of 1,100 times. This would require a quite elaborate circuit.

Because of this difficulty in mechanically controlling high radio frequencies, early transmitters employed an oscillator of the feedback type working directly into an antenna with a consequent high degree of frequency *instability*. To avoid the reaction of the load on the oscillator or frequency generating source, radio-frequency amplifiers were added between the oscillator and the antenna. With care, such circuits may be made to function with excellent frequency stability.

After years of research, there was discovered and perfected a mechanical oscillator which could be made to closely control the output of an oscillator without the need of expensive frequency multiplying equipment. Such an oscillator is called a crystal controlled oscillator, the most popular crystal being quartz. The operation of such a device is dependent on an effect known as the "piezo-electric" characteristic of certain crystalline substances, and this effect is exceptional in quartz, tourmaline and Rochelle Salt crystals.

The "piezo-electric" effect is said to have been known to Coulomb in 1780, but was not so designated until 1881 when Hankel applied this name to it. Becquerel published quantitative results regarding it in 1833 and J. and P. Curie performed certain experiments on quartz in 1880. Dr. W. G. Cady, now at Wesleyan University, developed the basic circuit which made the piezo-electric effect practical and he is really the father of modern crystal control of radio frequencies.

Piezo-electric means pressure-electric and substances which are active, piezo-electrically, exhibit this effect. It means simply that a mechanical pressure properly applied to certain faces of the crystal will cause a difference of potential to appear across those faces. The converse is also true, namely that a difference of potential applied across the faces will alter the shape of the crystal physically.

This piezo-electric effect is present in all substances having a crystalline formation but as has been stated, is much more pronounced in some substances than in others. Tourmaline is a semi-precious stone and is somewhat expensive for commercial use; it is also difficult to obtain in a large size and in large quantities. Tourmaline is sometimes used for very high frequency crystals because its thickness-frequency coefficient is greater than quartz. This permits the crystal, for a given high frequency, to be thicker and hence more rugged than a corresponding quartz crystal. (By crystal, in most of the discussion that follows, is meant a slab or plate properly cut from the mother crystal. It is customary to refer to such a plate as a "crystal").

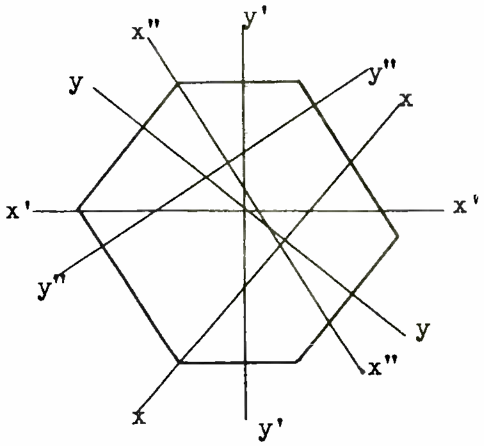
A Rochelle salts crystal has probably the most pronounced piezo-electric effect and the crystals can be grown commercially in a short time to almost any desired size in a super-saturated solution of the salts. The outstanding disadvantage of the Rochelle salts crystal for the control of radio frequencies is its physical sensitivity to temperature changes and its ability to absorb moisture from the atmosphere and thereby vary in dimension. Also, if allowed to get too warm it will absorb moisture and disintegrate like a lump of sugar. The piezo-electric effect of this substance is so pronounced that a crystal several inches in length may be twisted between the hands and on being released may generate a difference of potential as high as 700 volts. The voltage of course must be measured by means of an electrostatic voltmeter as the actual amount of power developed is extremely small. Rochelle salt crystals are extensively used commercially as the voltage generating device in microphones and pickups. Such units can be made to have excellent frequency characteristics.

With tourmaline and Rochelle salts eliminated from consideration in radio-frequency control on a commercial basis there is left only the quartz crystal for practical use. Quartz possesses the good qualities of both of the other substances and in addition is very hard, impervious to moisture, can be cut and ground to any desired dimensions, and can be obtained in comparatively large quantities at such a price as to make its use entirely practical. Quartz crystals are mined in Madagascar, Brazil, various parts of the United States and in other parts of the world.

While the "piezo-electric" effect of crystals had been known for many years, it was put to no practical use until experimenters during World War I developed the idea of using piezo-electric crystals to control the frequency of a vacuum tube oscillator. Professor Cady, then at Harvard University, did the early development work in this field.

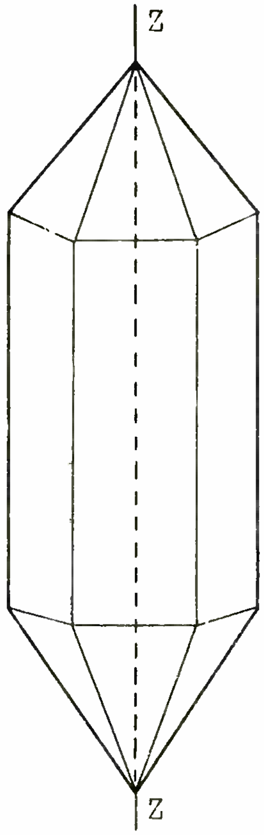
Quartz crystals are the result of thousands of years of growth under pressure. Quartz crystals are *always* found in the same form, hexagonal in shape with a sharp apex on each end. In mining, the crystal is frequently broken from the rock on which it was growing and one or both of the points broken off, but the complete crystal is always in the form shown in Figs. 1(A) and 1(B) and the opposite sides are always parallel, but seldom identical in length. 1(A) shows a cross-section and 1(B) shows a side view.

Each crystal has three axes or planes along which pressure may be applied. The X axis is parallel to a flat side of the crystal as shown in Fig. 1(A). If the crystal happens to be a regular hexagon the plane of the X axis will intersect opposite corners but that is not the usual condition and does not occur in 1(A). The Y axis is normal (perpendicular) to the flat side of the crystal. Each Y axis is perpendicular to an X axis. Thus, in Fig. 1(A), y is perpendicular to x, y' is perpendicular to x', and y" is perpendicular to x". Thus, there is one Y axis for each X axis. The Z or optical axis is a line drawn between the two apexes of the crystal as shown in Fig. 1(B). The Z axis is at right angles to both the X and Y axes.



(A)

Fig. 1.—Cross-sectional view of quartz crystal.



(B)

Side view of quartz crystal.

The X and Y axes are called the electrical axes of the crystal because if a difference of potential is applied across either axis the crystal will contract along that axis and expand along the other axis. The Z axis is called the optical axis and shows no electrical effects; i.e., if a difference of potential is applied along the Z axis the crystal will not be compressed. Conversely, if a mechanical pressure is applied along the X or Y axis a difference of potential will be established when the pressure is removed; if such a pressure is applied along the Z axis no difference of potential will result.

Fig. 2 shows an actual crystal just as it is received at the crystal laboratory for inspection and cutting. The lower end has been cut off in a preliminary cut, but the general shape of the crystal is clearly shown. The horizontal lines or streaks are "growth lines". The Z axis is in a vertical plane through the apex.

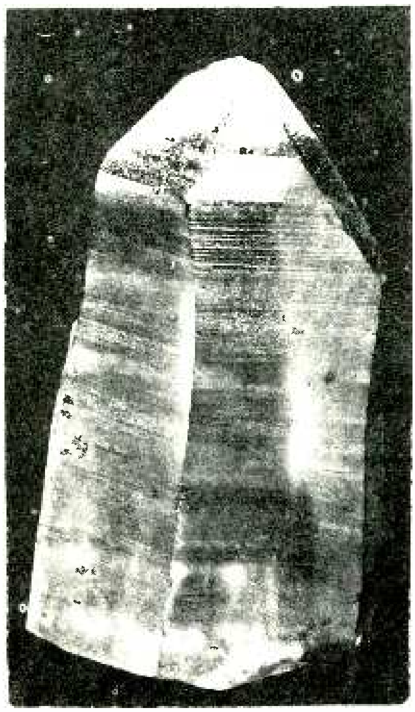


Fig. 2.—View of crystal ready for cutting.

Fig. 3 shows a slab taken from the crystal in the first cutting operation. This slab clearly shows the hexagonal form of the crystal. A comparison with Fig. 1(A) will make clear the directions of the X, Y and Z axes in the actual crystal. The slab as shown is slightly more than one inch thick and the large flat surfaces (top and bottom) have been cut perpendicular to the Z axis.

Fig. 3.—View of crystal slab cut from crystal.

There are several methods of cutting a crystal to take advantage of its piezo-electric oscillations for frequency control.

X CUT CRYSTAL.—This was the cut most commonly used for high frequency operation before the advent of special low temperature frequency coefficient cuts and is used quite extensively at lower frequencies. A particular advantage of the X cut crystal is that, when properly cut, it will vibrate at two fundamental *and widely separated* frequencies, one being determined by the X or thickness dimension, the other by the Y or length dimension. To make a practical use of the crystal in the control of frequency, the crystal is cut in a rectangular (usually) form so that the dimensions of either the X or Y axis is such that the *mechanical* vibrations of the crystal will be of the desired frequency.

A quartz crystal will vibrate along its X axis (this is the thickness dimension if X cut) at a frequency determined as follows:

$$f = \frac{k}{t}$$

Where

f = frequency in cycles

$k = 113 \times 10^6$ (the frequency constant for X cut plates)

and

t = the thickness dimension in mils. (thousandths of an inch)

If the thickness dimension is in mils, the expression may be used to determine the approximate natural frequency of a plate by substitution of the thickness for t. Thus a plate whose thickness dimension is the X axis would have a natural frequency of 1,000,000 c.p.s. if it were 113 mils thick. This is so because

$$f = \frac{113 \times 10^6}{113} =$$

$$10^6 \text{ cycles or } 1{,}000 \text{ kc/s}$$

This expression may also be written

$$f = \frac{113}{t}$$

where

f = frequency in mc/s
t = thickness in mils

If the plate is 1 millimeter thick, this dimension must be converted to mils. From the English-Metric system, 1" = 2.54 centimeters, abbreviated cm. Also 1" = 25.4 millimeters, abbreviated mm. Hence 1,000 mils = 1" = 25.4 mm. So 1 mm = 1000/25.4 = 39.37 mils. For this thickness, an X cut crystal would have a natural frequency of

$$f = \frac{113 \times 10^6}{39.37} =$$

$$2.87 \times 10^6 \text{ cycles/sec. or } 2870 \text{ kc/s}$$

From this, one may also determine the wavelength constant for the X cut plate. The fundamental relation between frequency and wavelength is $f\lambda = 3 \times 10^8$, the velocity of light, for electromagnetic vibrations. Hence the wavelength per millimeter of thickness must be

$$\lambda = \frac{3 \times 10^8}{2.87 \times 10^6} = 104.5 \text{ meters per mm}$$

This expression is little used.

If the crystal were 5 mm thick, it could be made to vibrate along its X axis at 2870/5 = 574 kc/s corresponding to a wavelength of 104.5 × 5 = 522.5 meters.

The crystal can also be made to vibrate at a frequency corresponding to its Y dimension. For this vibration $K = 107 \times 10^6$. If the Y dimension is 1 mm,

$$f = \frac{107 \times 10^6}{39.37} =$$

$$2.718 \times 10^6 = 2718 \text{ kc/s}$$

$$\lambda = \frac{300 \times 10^6}{2.718 \times 10^6} = 110 \text{ meters/mm}$$

If the Y dimension of the X cut crystal is 25 mm (slightly less than

1 inch) the frequency of vibration will be 2718/25 = 108.72 kc/s corresponding to a wavelength of 110 × 25 = 2750 meters. Thus, a crystal having X dimension = 5 mm and Y dimension = 25 mm can be made to vibrate at either 574 or 108.72 kc/s per second.

The crystal also can be made to vibrate at a frequency somewhere between the X and Y frequencies, the third frequency being called the coupling frequency. The coupling frequency is a function of all the dimensions of the crystal and is never put to practical use because of the difficulty in predetermining the dimensions necessary to give an exact desired frequency.

The crystal vibrations are actual mechanical vibrations and may be so violent as to shatter the crystal. Just as a piece of metal, or in fact every object, has some period of vibration, so has the quartz crystal and that period of vibration is a function of the dimensions of the crystal; the larger the dimensions, the slower the period of vibration.

From the above it will be seen that it is necessary to cut a piece of certain dimensions from the quartz, those dimensions to correspond approximately to the dimensions necessary to give the desired frequency. It will also be seen that each dimension must be cut to correspond to one axis of the crystal.

The "X Cut" crystal is cut in the following manner: first a section about one inch thick is cut across the crystal at right angles to the Z axis. This is shown in Figs. 3 and 4. Figures 3 and 5 show the section removed from the mother crystal of Figs. 2 and 4. Figure 5 also shows the next step in the operation. A slice is cut out of the original section. *The length of the slice is along a Y axis. The thickness of the slice corresponds to the X axis*, and the third dimension of the slice is along the Z axis. Such a crystal is called an "X *Cut*" crystal.

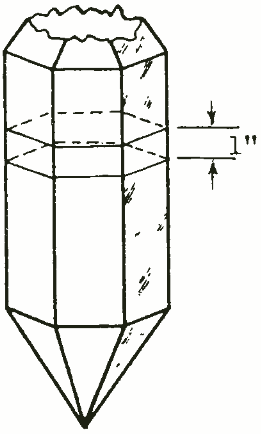


Fig. 4.—Method of cutting X-Cut crystal slab.

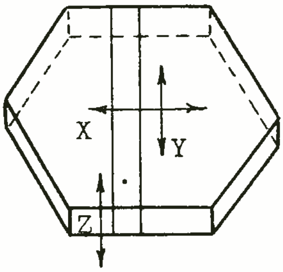


Fig. 5.—Second step in cutting X-Cut crystal slab.

It has been shown that the

crystal can be made to vibrate at a frequency corresponding to the dimensions of either its X or its Y axis. With the method of cutting described above the Y dimension will be large compared to the X dimension. When a low frequency (long wavelength) is desired the Y vibration of the crystal is used; for shorter wavelengths (higher frequencies) the crystal is made to vibrate along its X axis. For low frequency operation the Y dimension is usually made longer than the Z dimension with the X dimension comparatively thin. This type of crystal is shown in Fig. 6. If the Y dimension is 40 mm, the frequency will correspond to a wavelength of about 4400 meters or 68.2 kc/s.

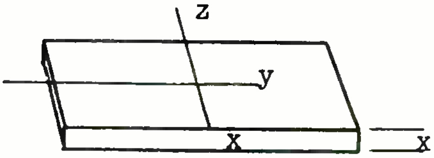


Fig. 6.—Low frequency X-Cut crystal.

When a high frequency is desired the X dimension is used and the crystal is nearly square, i.e., the Y and Z dimensions are approximately equal. This type of crystal is shown in Fig. 7. If a wavelength of 75 meters is desired the X dimensions should be approximately 75/105 mm, since it has been shown that an X cut plate 1 mm thick has a wavelength constant of approximately 105 m/mm and the *wave length is directly proportional to the thickness.*

The crystal is cut to somewhat greater than the desired dimensions by machine and then ground to the exact dimensions. The first of the grinding is done by machine and then the final grinding to the exact frequency is done by hand. This final grinding must be done very carefully because at high frequencies a slight touch of the grinding compound will change the frequency an appreciable amount. When the correct frequency is almost reached, the crystal is tested very frequently for frequency and ability to oscillate, until the exact desired frequency is obtained. This final precise work is the reason why a crystal ground to an exact frequency is expensive.

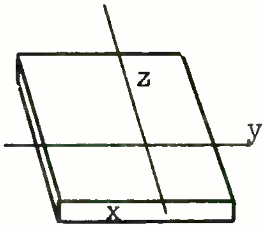


Fig. 7.—High frequency X-Cut crystal.

The finished crystal must be perfectly regular, all parts being of the same thickness, with no scratches, cracks or other irregularities. A crystal will sometimes oscillate with slight irregularities but will not deliver the maximum power under such conditions.

In common with all simple mechanical vibrating devices in which the frequency of vibration is a function of the dimensions, the oscillating frequency of the X cut crystal varies with a variation of crystal temperature. As the temperature of the crystal is increased the crystal expands. In the X cut crystal this results in a *decrease* of frequency. That is, the temperature-frequency coefficient of the crystal is negative. For such a crystal operating on its X axis, the frequency varies from 20 to 25 parts in a million for each degree Centigrade change in temperature. When an X cut crystal is vibrating at its Y axis frequency, the frequency variation per degree Centigrade will be about 10 parts in a million.

Thus, the frequency of such a crystal operating on its X axis at 1000 kc/s will vary about 25 cycles per each degree Centigrade temperature change. If the temperature increases 10° the frequency will decrease about 250 cycles. Since the *maximum* allowable frequency deviation in the broadcast band is 20 cycles, it is seen that such a device without temperature control is far from a constant frequency generator. If the operating frequency were 20,000 kc/s instead of 1000 kc/s, the same 10 degrees variation in temperature would cause a frequency variation 20 times as great or about 5 kc/s.

To provide constant frequency control, the crystal is ordinarily operated in an oven with thermostatic control at a temperature somewhat higher than that ever encountered under normal operating conditions—usually about 50° C. Such a device allows the crystal temperature to be held within a small fraction of one degree of the desired temperature and hence permits quite accurate control of frequency.

THE "Y CUT" OR 30 DEGREE CRYSTAL.—The "Y Cut" crystal is cut from a slab of quartz similar to that shown in Figs. 3 and 5, but the slice is made parallel to an X axis instead of parallel to a Y axis as in the case of the X cut crystal. Thus, in the Y cut crystal the thickness dimension is along the Y axis. The two cuts are shown in Fig. 8.

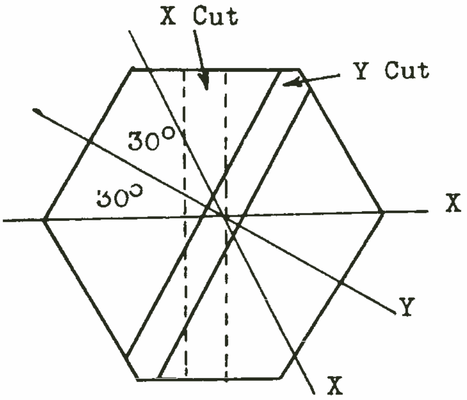


Fig. 8.—Y-Cut crystal slab compared to X-Cut.

In the Y cut crystal, the frequency of the thickness oscillation is not a simple matter as in the X cut crystal in which the X axis is perpendicular to the face of the crystal. In the case of the X cut crystal vibrating at its thickness frequency there is only one frequency involved, the other X axes being displaced by 60 degrees and the Y axis being a large dimension compared to the X axis. In the case of the Y cut crystal the problem is considerably more involved. Fig. 8 illustrates the manner in which the Y cut slice of crystal is removed from the slab. It also shows that, while the thickness of the crystal is along a Y axis, there are *two X* *axes displaced only 30° from the Y axis.*

Under this condition there are several possible modes of vibration. Vibrating at a frequency controlled by the thickness Y axis, $K = 78 \times 10^6$. For a 1 mm thickness,

$$f = \frac{78 \times 10^6}{39.37} =$$

$$1.981 \times 10^6 = 1981 \text{ kc/s}$$

$$\lambda = \frac{300 \times 10^6}{1.981 \times 10^6} = 151 \text{ Meters/mm}$$

Another useful expression for the Y cut is

$$f = \frac{78}{t}$$

where

f = frequency in mc/s

t = thickness in mils

However, Fig. 9 shows there are two X axes displaced only 30° from the Y axis, one on each side, and the crystal will vibrate very easily at the thickness X dimension, particularly if the two X axes are of exactly the same length through the crystal, both intersecting the Y axis at the center of the crystal. In that case their piezo-electric effects will add in a direction along the Y axis and the strength of oscillation for a given applied voltage will be greater than in the X cut crystal where a single X axis is concerned. If the two X axes through the crystal are not *exactly* the same length there will be two X frequencies very close together and the crystal may oscillate at either frequency, even with a fixed plate tank circuit adjustment.

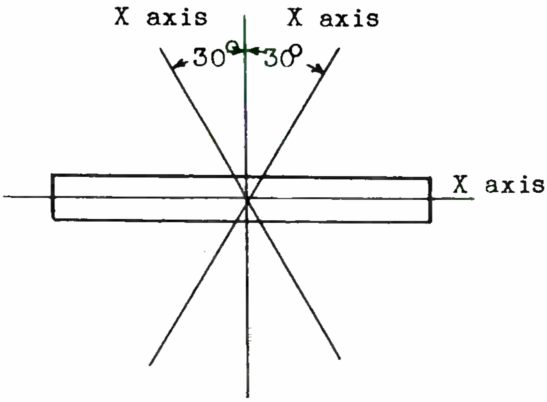


Fig. 9.—X-vibration in a Y-cut crystal.

The X vibration frequency in a Y cut crystal will still correspond to 104.5 meters/mm of X axis dimension. However, as is clearly shown in Fig. 9, the length along the X axis is greater than the thickness, being equal to,

$$\text{X dimension} = \frac{\text{Thickness in mm}}{\text{Cos } 30^\circ} =$$

$$\frac{\text{Thickness}}{.866}$$

Thus, the X vibration in a Y cut crystal will be equal to that of an X cut crystal 1.155 times as thick, and for a crystal 1 mm thick, $\lambda = 104.5 \times 1.155 = 120.7$ meters. This may be compared with 151 meters per mm along the Y axis as calculated above.

In the Y cut crystal, due to the several possible modes of operation and the combinations of frequencies and their overtones that may be present, the length and width of the crystal have a considerable bearing on the thickness frequency of oscillation—much more so than in an X cut crystal.

All of these factors tend to make the cutting and grinding of a Y cut crystal an erratic problem. As the crystal is being carefully ground approaching the desired frequency, it may be tested, then ground very slightly, tested again and the frequency found to have jumped a number of kilocycles. It is then necessary to work on a width or length dimension until the proper frequency again predominates before work on the thickness can be resumed. A similar discontinuity exists in the temperature frequency curve. That is, if the crystal temperature is varied over a considerable range, instead of the frequency varying over a smooth curve, at intervals the curve will be broken and displaced along the frequency axis, the succeeding portion of the curve continuing from the new position. This is shown in Fig. 10.

The temperature coefficient of the Y cut crystal is *usually* positive and is somewhat larger than that of the X cut crystal. In the ordinary frequency bands, when operated at the thickness vibration, the temperature coefficient is usually between 75 and 125 parts in a million and is *positive*—that is, the frequency increases with an increase of temperature. On the other hand, the long electrical dimension of the Y cut crystal has a negative temperature coefficient similar to that of the X cut crystal.

It is not known definitely why the Y cut crystal has a positive temperature coefficient. However, any crystal must be thought of as a very complex arrangement of coupled circuits, the different circuits all having different frequencies and with all degrees of coupling existing. Just as a group of closely coupled circuits react on each other, so do the various dimensional frequencies of the crystal.

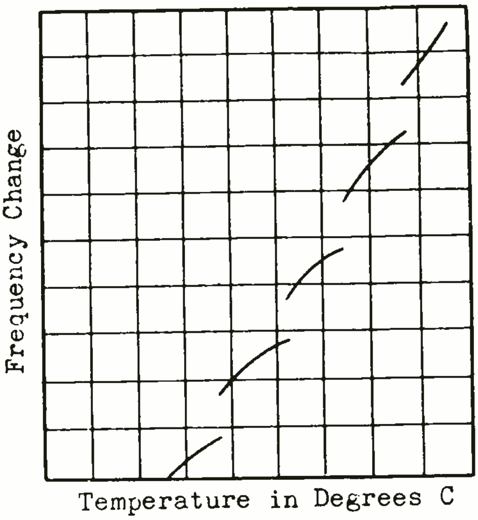


Fig. 10.—**Temperature variation of frequency for a Y-Cut crystal.**

By so varying the dimensions and shape of the crystal with respect to its electrical axes it is possible to make the temperature—frequency coefficient positive or negative and large or small. Where a constant frequency is of greater importance than power output very odd crystal shapes are sometimes employed. Both the Bell Telephone Laboratories and the Bureau of Standards have done considerable work with crystals cut in the form of a ring. The present frequency standards of the Bureau of Standards employ ring shaped crystals.

The Y cut crystal is used quite extensively in broadcast work because, since oscillations may be started easily, it can be used with a quite low plate voltage. Some radio engineers greatly prefer the X cut crystal—others just as strongly prefer the Y cut. If carefully prepared either can be made to perform satisfactorily.

AT CUT CRYSTAL.—A consideration of the regular X cut and Y cut crystals show that not only the frequency of vibration but also the temperature coefficient of a crystal is a complex function. In the X cut crystal the X frequency variation per degree Centigrade is about 25 parts in a million and is negative, the Y frequency variation is about 10 parts in a million per degree Centigrade and is negative. In the 30° Y cut crystal the frequency variation with temperature is about 100 parts in a million and is positive. It would seem that some angle of cutting could be found that would be a compromise between the positive and negative temperature coefficients and allow practically zero temperature coefficient. This effect has been accomplished for some years by means of oddly shaped crystals such as the ring mentioned above. This, however, is impractical from the viewpoints of cost, mounting methods required, power output, etc., for any but laboratory purposes. What is really required is a relatively inexpensive rugged crystal which may be clamped in an ordinary type of holder, subjected to quite wide variations of temperature in ordinary service and still have negligible frequency drift.

An airplane installation forms an outstanding example of such a requirement. A plane may leave the ground in a temperature of 100° F and in the course of less than an hour be flying at a high altitude where the temperature may be below zero. With either an X or Y cut crystal at even the medium high frequencies such a temperature variation would cause a drift of perhaps several kilocycles, necessitating the use of a constant temperature unit which adds both weight and complexity to an installation which inherently should be both simple and light.

To provide such a crystal Bell Laboratories conducted extensive experiments on crystals cut at all angles and shapes until finally the so-called "AT" cut crystal was announced in July, 1934, and has proved very successful in subsequent commercial operation.

The AT cut crystal minimizes two seriously undesirable features of the Y cut crystal. First, the temperature-frequency coefficient of the Y cut crystal of from 75 to 125 parts in a million per degree Centigrade is reduced to an amount which for most purposes is negligible in the range of temperatures ordinarily encountered. Second, the frequency of a Y cut crystal does not vary linearly and continuously with temperature variation. Over a certain small range of temperatures the variation will be essentially linear, then with a slight additional variation there may be a jump of several hundred cycles, continuous for another small temperature range, then another jump, etc. This is not a serious disadvantage if the crystal is operated with good temperature control but for operation without controlled temperature it becomes serious. This discontinuity of frequency with temperature variation is caused by the complex vibrations of the crystal, harmonics of the low frequency vibrations, etc. By suitable change of the cutting angle with respect to the crystal axes, (X, Y and Z), most of these undesired vibrations are minimized and in addition to extremely low temperature-frequency coefficient, the discontinuity of the temperature-frequency curve is eliminated in the range of practical working temperatures.

Figs. 11, 12, and 13 which are reproduced from the Bell System Technical Journal clearly show the manner in which the AT cut crystal is cut. Fig. 11 shows the original quartz crystal with a convential Y cut section as it will be removed in the process of cutting. Fig. 12 shows the same Y cut section after it is removed from the slab, the thickness dimensions being along the Y axis perpendicular to both the X and Z axes. This is seen to be identical to the crystal of Figs. 8 and 9.

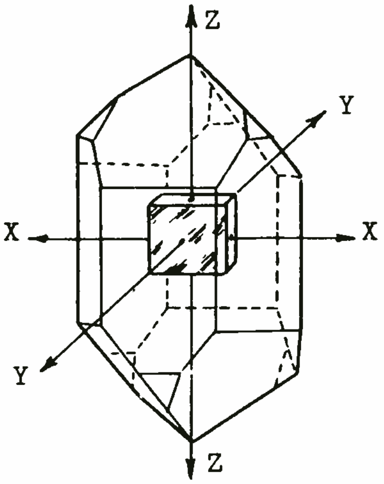


Fig. 11.—Y-Cut crystal in mother crystal showing how it is cut.

Fig. 13 shows the change in the cut used to produce the AT cut crystal. The cutting angle is rotated θ° around the X axis. In the AT cut crystal θ = 35°. Thus, the thickness dimension Y′, or rather a line perpendicular to the face of the crystal through the thickness dimension, is removed 35° from the Y axis of the crystal. The longitudinal X axis is unchanged because the rotation is around this axis, and the Z′ dimension is removed 35° from the Z axis of the crystal.

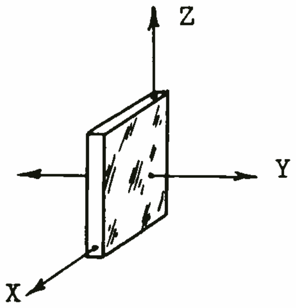


Fig. 12.—Y-Cut crystal slabs.

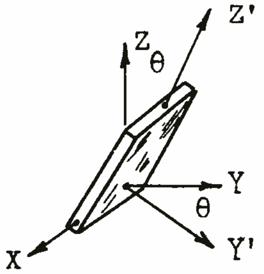


Fig. 13.—Showing how AT-Cut compares to Y-Cut slab.

The frequency of the AT cut crystal varies only a few cycles for a quite wide variation of temperature and like the Y cut crystal it may be clamped in the holder. Thus, it is very applicable for aircraft operation without the necessity of using a constant temperature unit, and for operation in any transmitter where its characteristics will be of advantage.

Due to the reduction in spurious frequencies with their accompanying stresses through the crystal, the AT cut crystal may be operated at greater output than may the Y cut crystal without danger of cracking. This is a real advantage at the higher frequencies where the thickness of the crystal is not great and the crystal is thus fragile and easily broken. Oscillator outputs of 50 watts and more have been obtained at 2,000 kc/s.

A convenient expression relating frequency and thickness in the AT cut crystal is

$$f = \frac{66.2}{t}$$

where

f = frequency in mc/s

t = thickness in mils

BT CUT CRYSTAL.—This is a trade designation for a low temperature coefficient crystal developed by the Bell Telephone Laboratories. The major face is parallel to an X axis but forms a -49° angle with the Z axis. The BT cut expression relating thickness and frequency is

$$f = \frac{100}{t}$$

where

f = frequency in mc/s

t = thickness in mils

Since the constant in the numerator is larger for this cut than for the AT cut, it is more suitable for making higher frequency crystals since a BT cut will be thicker and thus more rugged for a given frequency.

AC CUT CRYSTAL.—This is also a development of the Bell Laboratory. In this cut, the face is parallel with the X axis and forms a 31° angle with the Z axis. In this cut

$$f = \frac{66}{t}$$

where

f = frequency in mc/s

t = thickness in mils

BC CUT CRYSTAL.—This is also produced by the Bell Telephone Laboratories. The face is parallel with the X axis but makes a -60° angle with the Z axis. In this cut

$$f = \frac{102}{t}$$

where

f = frequency in mc/s

t = thickness in mils

V CUT CRYSTAL.—This is a trade designation for a cut developed by the RCA Manufacturing Co., Inc. Unlike other low temperature coefficient crystals the major surfaces of the V cut crystals are not parallel to either the X, Y or Z axes.

SUMMARY OF TEMPERATURE RANGES FOR THE CUTS.—The TC (temperature coefficient expressed in cycles/megacycles/degree C of temperature variation) is approximately -22 for crystals in the 400 to 20,000 kc/s range. For frequencies between 50 and 500 kc/s, the TC is also approximately -22 cycles per megacycle per degree Centigrade. When the ratio of the Z dimension to the Y dimension (Z/Y) is less than .2, TC is -7, and as Z/Y becomes greater than 1, TC may reach -50. With certain Z/Y ratios, TC may lie between ±2 to 5. Y CUT: TC varies from -20 to +100. AT CUT: TC = ±2. BT CUT: TC = ±2. AC CUT: TC = +20. BC CUT: TC = ±20. V CUT: From 50 to 500 kc/s, TC = .1 to 2.0. In the broadcast range, TC is less than 1.5 and from 1,600 to 20,000 kc/s, TC is less than 2. The temperature coefficient versus rotation about the X axis is shown graphically in Fig. 14.

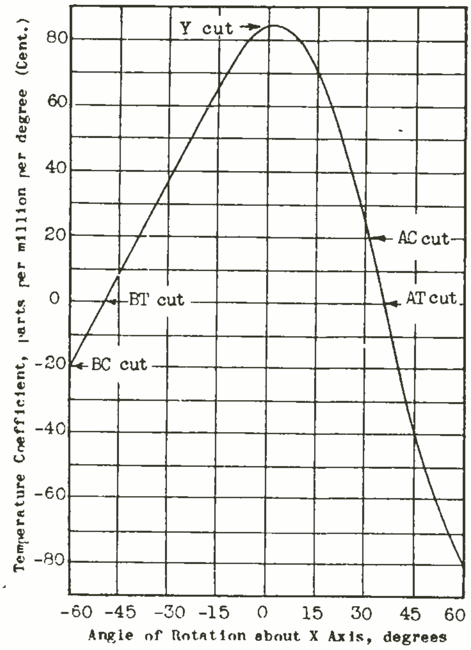


Fig. 14.—Temperature coefficient variation with angle of cutting slab.

The fundamental frequency of vibration for any of these cuts is given by the expression

$$f = \frac{1}{2t}\sqrt{\frac{C_{66}}{p}}$$

where C_{66} = the elastic constant for quartz. This varies from 28×10^{10} to 70×10^{10}, depending on the angle of rotation about the X axis.

t = thickness in centimeters

p = density of quartz (2.65 grams per cubic cm.)

Fig. 15 shows a slab of raw crystal and a number of cut crystals of various shapes and dimensions. The long bars are low frequency crystals which are operated at the length dimension. Crystals to operate at frequencies of 100 kc/s or lower are usually in bar form For higher frequencies the plate form is ordinarily used.

CARE OF THE CRYSTAL.—Extreme care should be taken in handling the crystal. High frequency crystals are very fragile and easily broken, and even the larger crystals cut for the lower frequencies may be chipped by careless handling. A crystal will seldom oscillate with any chipped place or irregularity on it. If a crystal should become chipped on the edge and refuse to oscillate, that edge of the crystal may be carefully ground down with very fine powdered emery on a perfectly flat surface until the edge has been ground down past the irregularity. If the grinding is done carefully and evenly along the entire edge, the crystal should again oscillate satisfactorily although at a slightly different frequency. Where an exact frequency is required the damaged crystal should be replaced with a new one.

The crystal should always be kept perfectly clean and should not be touched with the hands. Even finger prints on the crystal will seriously affect its operation and may entirely prevent oscillation. Whenever it is necessary to handle the crystal it should be thoroughly cleaned before being returned to the crystal holder. Either pure grain alcohol or carbon tetrachloride may be used for this purpose.

THE CRYSTAL HOLDER.—There are a number of types of good crystal holders designed for the different types of crystals. As shown in Fig. 15 crystals are ground in many shapes and sizes, the different shapes and sizes requiring different types of mounting. The crystal holder design is also influenced greatly by the type of crystal; that is, X cut, AT cut, etc. An X cut crystal will not oscillate if its edge movement is restricted in any way. In fact, it will often fail to oscillate if its edge merely touches the side of the holder. On the other hand, Y cut and AT cut crystals may be actually clamped in the holder at their edges. This is a decided advantage where the crystal is used in an airplane transmitter or wherever it may be subjected to vibration.

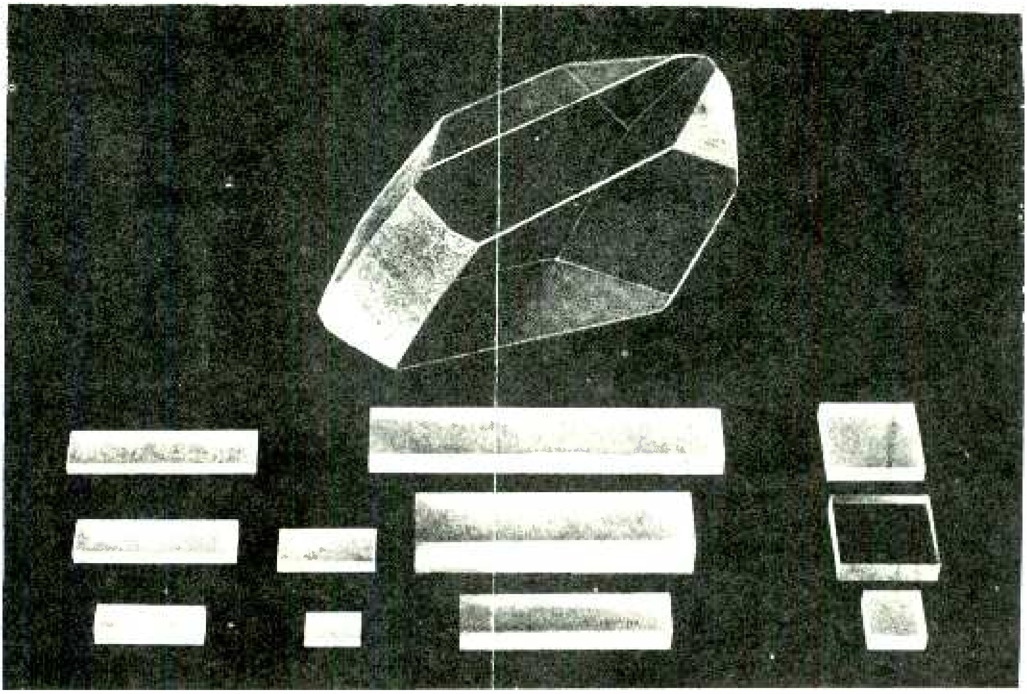


Fig. 15.—Various types and shapes of crystals.

For the unclamped crystal the basic parts of the holder consist of two metallic plates. The lower plate is heavy with a perfectly plane surface upon which the crystal is to rest. The upper plate should consist of a small metal plate of light weight also having a perfectly plane surface. If the upper plate is too heavy it will not allow the crystal to vibrate freely; on the other hand, if it is not heavy enough it will not rest firmly on the surface of the vibrating crystal. Crystal holders are designed for crystals of specified sizes and the top plate is properly proportioned for the crystal to be used. The upper plate is connected to the external terminal by means of a small *flexible* wire.

The crystal holder must be large enough to allow a small clearance on all sides of the crystal. This is important because when a crystal contracts along one axis it expands along another and if it does not have sufficient room in which to expand freely it cannot oscillate. The holder should not be too large, otherwise, the crystal will tend to slide around within the holder. Just sufficient clearance should be allowed to permit the crystal to vibrate freely.

When a crystal refuses to start oscillating it may at times be started by tapping the crystal holder *lightly*. The crystal may be close against one side of the holder and the light tap will give it clearance.

The crystal holder should be dust and moisture proof. The two terminals should be plainly marked grid and filament; the grid terminal connects by a flexible wire to the *upper* crystal contact and the filament terminal to the lower brass plate.

There are certain operating conditions where the crystal is subject to considerable vibration, such as in an airplane installation. In such an installation the crystal may often have to operate at all angles. Thus, crystal holders have been developed in which the crystal is clamped firmly in place rather than being subject to movement as explained above. The AT cut crystal is ordinarily used in such installations. Clamping the crystal may reduce its output but with proper holders does not affect it. This may be relatively unimportant because high gain buffer stages may be used to build up the small output. Somewhat similar holders are often used with low frequency crystals in crystals controlled standard frequency oscillators. Adjustment of the crystal frequency *over a limited range* is possible with such a holder because variations of the pressure applied to the upper plate by a screw adjustment vary the air-gap between plate and crystal and cause slight variations of the capacity across the crystal. If the pressure is either too great or too small the crystal will not oscillate. Adjustment may be made between those extremes.

Figs. 16 to 20 inclusive illustrate several types of commercial crystal holders. Note that in Fig. 17, the holder is arranged so that it can be sealed to prevent tampering. Fig. 20 illustrates a holder designed specifically for a 50 kc crystal. The crystal in this case consists of an X cut bar oscillating at its length or Y dimension. The crystal is placed on edge between the two long plates and clamped between two screws at the geometrical center of the largest faces—that is, along the X axis. The voltage is applied across the two plates, and hence along the X axis, and longitudinal vibrations occur at the Y frequency. Adjustable baffle plates are provided at each end of the holder to minimize the effect of air waves radiated from the ends. Similar but longer holders are available to accomodate crystals having frequencies as low as 20 kc/s.

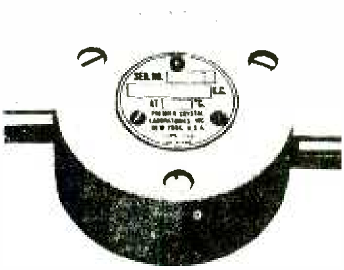


Fig. 16

Fig. 17

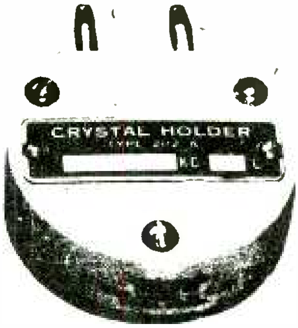


Fig. 18

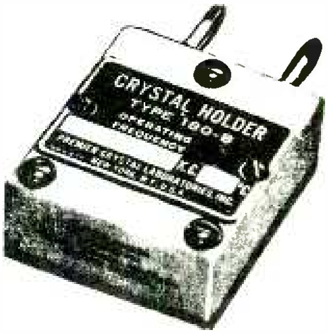


Fig. 19

Fig. 20

Commercial types of crystal holders.

In the crystal holder of Fig. 16, the base plate and all internal parts are of monel metal. In the holders of Figs. 17, 18, and 19, the metal parts are of nickel silver. In the holders of Figs. 16 to 19 inclusive, the covers are of glazed isolantite as is the base of the holder in Fig. 20. All the metal parts of the holder in Fig. 20 are heavily nickel plated.

SOME THEORETICAL CONSIDERATIONS.—In any practical circuit, the crystal is never used alone, it must always be employed with a pair of flat plates in more or less intimate contact. It is usual to consider the equivalent electrical network of the crystal as shown in Fig. 21. L_1 represents the inductance, the electrical equivalent of mass in the mechanical circuit. C is the capacitance or the mechanical resilience. C_1 is the capacity due to the holder with the crystal acting as dielectric. C_2 is the capacity between the top plate and the crystal acting as a complete electrical unit. This last capacity will not be effective unless an air-gap type of holder is employed. R is the resistance and represents the frictional losses in the crystal. In the equivalent electrical circuit, the equivalent inductance values will be found to be surprisingly large, much larger than could be made in practice without running into excessive distributed capacity and resistance. While the resistance may seem very high, it must be recalled that it is the ratio of ωL_1 to R which is the quality factor of a coil or circuit and the quality factor, Q, will be very large, even with an apparently excessive R. For example, in a crystal resonant to 451.5 kc/s, the L_1 value is *3.656 henries* and the R value is 9,036 ohms.

$$Q = \frac{6.28 \times .4515 \times 10^6 \times 3.656}{9,036} =$$

$$1147$$

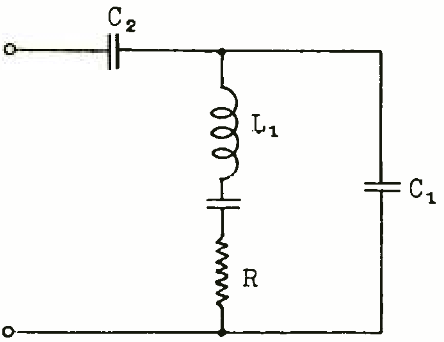


Fig. 21.——Equivalent electrical network of a quartz crystal.

It will be seen that a circuit with a Q of this value would be impractical in all except possibly a few expensive and bulky installations. The equivalent capacity C is found to be .0316 µµf and C_1 is 5.755 µµf.*

Despite the high value of resistance, the reactance is so many times larger, that the sides of the resonance curve will be very steep and the curve very narrow. This means an exceptionally selective circuit; also that a larger change in reactance is possible with but a small change in frequency. This gives an exceptionally stable circuit for controlling oscillation and, as a filter circuit, the selectivity is measured in cycles rather than kilocycles. In fact, selectivity may be obtained in the order of 50 cycles where a crystal filter is employed in receivers.

A study of Fig. 21 will reveal that there is a frequency, say f_1, for which the inductive and capacitive reactance of the left hand branch will be equal and the total reactance zero. This frequency will be called the natural resonant frequency of the crystal. There will also be some slightly higher frequency, f_2, where the crystal will become anti-resonant, that is will offer a very high value of opposition as in any parallel circuit.

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*From Terman "Radio Engineering", second edition, McGraw Hill Publishing Co., page 378.

This condition and the resonant condition are shown in Fig. 22.

In most practical crystal circuits where the crystal is used to control the frequency of oscillations, the crystal acts as a parallel or anti-resonant circuit. Such a circuit may be altered in frequency characteristic by a variation in C_1. This capacity is influenced by the actual capacity of the holder, the tube input and stray capacity, and the load impedance in the plate circuit. Anything which alters any of these will affect the output frequency. In practice, the frequency of the crystal oscillator may be varied a few cycles by a small variation in the plate output tuning or by the variation in plate voltage of a few volts or by an actual small shunting capacity across the crystal holder. This last scheme is frequently employed in modern broadcast transmitters where a change of a few cycles is desirable to maintain the transmitter output frequency exactly with the station monitor. The capacitor is of the order of but a few micromicro-farads and it must not be made too large, or the loading on the crystal is excessive and the output is shorted by the reactance of the capacitor.

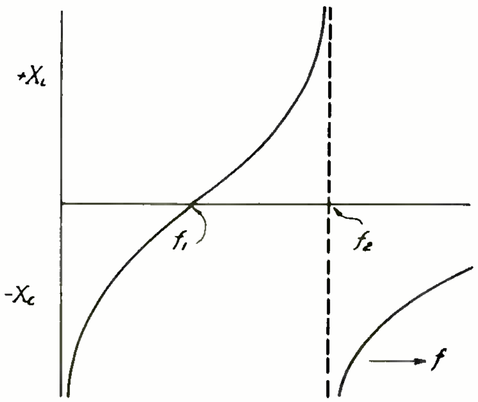


Fig. 22.—**Resonant and anti-resonant frequencies of a crystal.**

The output frequency may also be varied by a variation in the capacity of the air-gap where an air-gap holder is employed. This causes a change also in the value of C_2 and the actual condition is rather complicated. For small ranges of frequency, a variation in the air-gap is not harmful. If one attempts to carry the gap distance to too great values, the feed-back voltage necessary for oscillation becomes excessive and an arc may be developed between the top plate and the crystal with almost certain damage to the crystal.

The crystal may also be employed at its resonant frequency as a control of frequency but circuits of this nature are not usual. If the crystal is directly inserted in the tank circuit of an oscillator, the frequency at which the total reactance is zero, namely f_1, will allow the crystal to offer minimum impedance and the circuit will oscillate only at the crystal frequency. The crystal may also be placed in a path in series with the tuned circuit, possibly a preferable arrangement. See Fig. 23.

One of the most important uses of the quartz crystal is as a filter of exceptional characteristics where it is desired to pass a very narrow band of frequencies. It is costly and difficult to build such a filter of inductance and capacitance but the electrical characteristics of the quartz plate provide the necessary electrical network in excellent manner. The high Q of the crystal is responsible for its behavior. The crystal might be used as a filter in any type of circuit but it is most frequently employed in receivers of the superheterodyne type, in the intermediate frequency circuit. This is so because the intermediate frequency remains of a constant value for which a single crystal may be employed. In a receiver in which the radio frequency is variable, as in a tuned radio frequency type, a crystal filter would not be practical since a different crystal would be required for each separate frequency received.

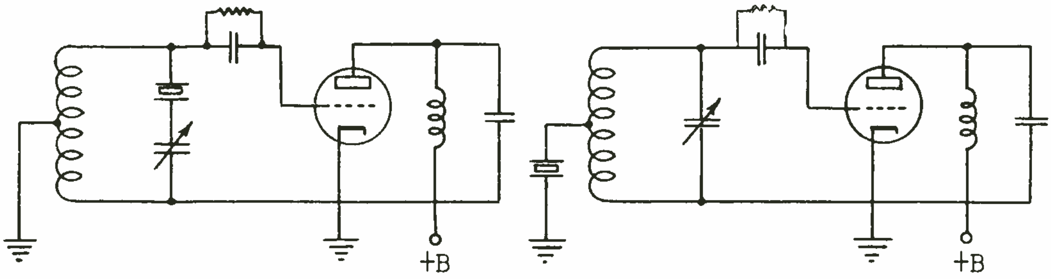


Fig. 23.—Methods of using crystals in a tuned circuit.

The usual circuit for receiver applications is shown in Fig. 24. It is usual to employ at least two intermediate frequency stages in such a receiver since the filter attenuates the intermediate frequency energy and makes the use of an additional stage desirable.

The usual procedure is to connect the crystal filter between the output of the mixer stage and the first i-f amplifier tube. Capacitors C_1 are the tuning capacitors for the primary or secondary of transformers T_1 and T_2. These are orthodox capacitors and require no explanation. C_2 is the phasing control, C_4 is the selectivity control and C_3 is the impedance matching control. Their functions and the theory of operation will be consider-

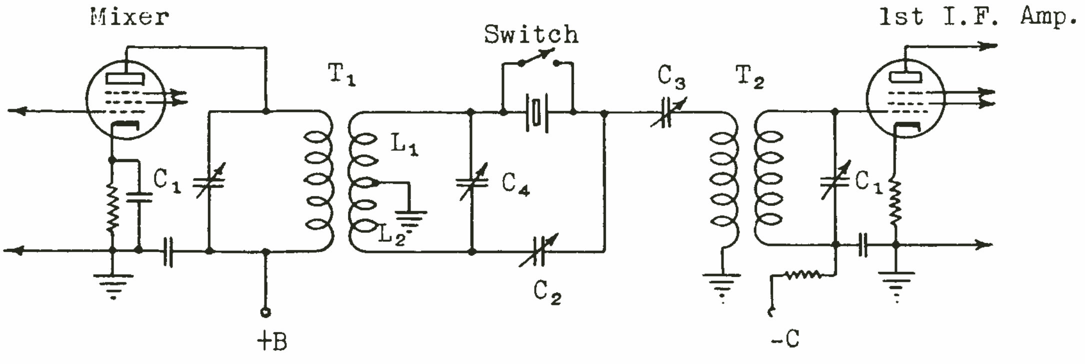


Fig. 24.—Crystal filter for receiver i-f amplifier circuit.

ed.

The circuit of Fig. 24 may be redrawn as shown in Fig. 25. It will be seen that what is actually present is a bridge circuit with the crystal in one arm and the phasing control C_2 in the other together with the sections of the secondary of T_1, one-half of which is in each arm. A variation of this arrangement is the use of a split-stator capacitor for C_4 and no center tap on the secondary. The two sections of the capacitor merely replace the two sections of the coil in the bridge. The principle of operation remains unchanged. When the bridge is balanced, the resonance curve for the crystal very closely approaches the ideal in symmetry. The extremely high Q of the crystal accounts for the narrow range of operation of the filter action. For frequencies at or very near to the series resonant frequency of the crystal, the bridge is unbalanced and the crystal containing arm passes these signals. For frequencies off the series resonant frequency of the crystal, the bridge is balanced and equal and oppositively phased voltages appear at B which neutralize each other. C_3 is used to match the output circuit to the crystal.

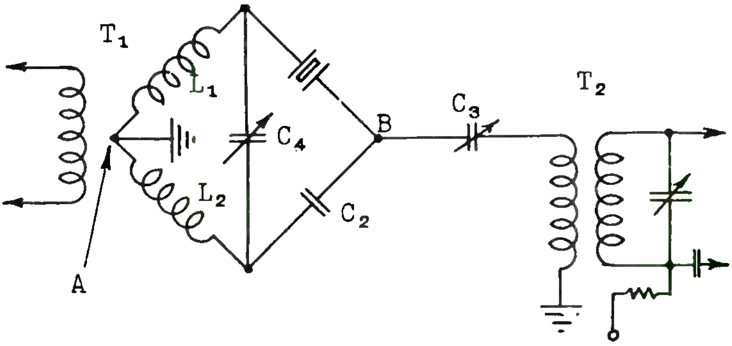


Fig. 25.—Redrawn to show it is a bridge circuit.

In circuits of the type discussed, variable selectivity is obtained by a variation in the setting of C_4. With the input circuit tuned to exact resonance, the secondary of T_1 and C_4 present a purely resistive load and this resistance is in series with the crystal. This increase in resistance makes the total circuit Q the lowest and hence the selectivity is least favorable. With the input circuit detuned from resonance, the resistive component of impedance drops rapidly and accordingly the selectivity increases rapidly. The selectivity may be varied over a range of about 10 to 1 with the maximum selectivity very much greater than could possibly be obtained in any other way. Since it may not always be desired to use the crystal, a switch is provided to short it out of the circuit. This switch is ordinarily a toggle switch mounted on the shaft with the selectivity control.

In a crystal filter circuit, the rejection possibilities of the parallel circuit may also be employed. With the crystal tuned to present a parallel circuit condition by means of the phasing control, the crystal may be used to reject an undesired frequency. This is useful in telephone work where this feature may be used to reject a strong carrier which is producing a bad heterodyne and at the same time still allow the use of the receiver in telephone reception.

Figs. 26 and 27 are reproduced by courtesy of the Hammarlund Manufacturing Co., Inc. and clearly illustrate the tremendous gain in selectivity by the addition of the quartz crystal filter. The outer curve of Fig. 26 shows the selectivity characteristic of the standard Comet "Pro." The inner curve shows the selectivity characteristic with the crystal in the circuit. The natural frequency of the crystal is 465 kc/s. All tuned circuits of the i-f amplifier are also carefully tuned to this frequency. The beat frequency oscillator for CW reception was adjusted to produce a 1,000 cycle beat note. The zero-beat area is shown at 464 kc/s and is illustrated as the gap in the curve. The inner or crystal filter curve shows the sharp peak and concave sides typical of all low loss single circuits. The convex shoulders at the lower part of the curve are caused by the i-f tuned circuits beginning to add subtantially to the over-all selectivity.

Along the dashed line labeled "Audio Image", which is interference on an i-f of 463 kc/s, it is observed that the strength of this interference is very much reduced from the value without the crystal in the circuit. Interference which produces an i-f of 467 kc/s will also give considerable reduced output. The signal ratios discussed are based on the assumption that the three signals have the same intensity. Such is rarely the case. In this discussion it may also be stated that the phasing control has been set to exactly neutralize the capa-

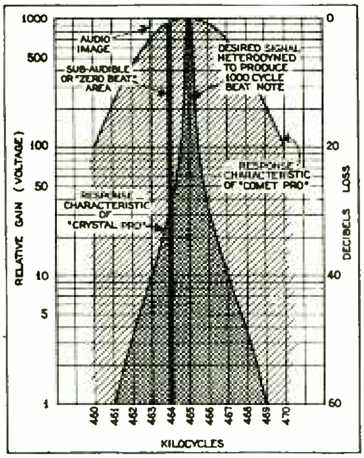


Fig. 26.—Selectivity of crystal filter.

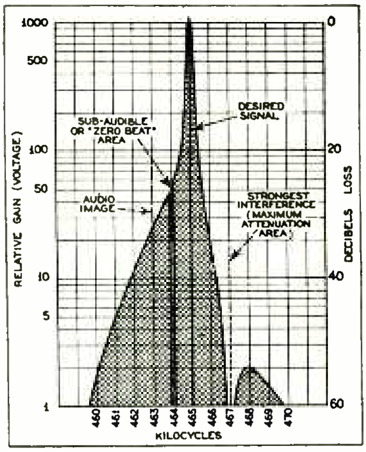


Fig. 27.—Selectivity using phasing control.

city of the crystal holder and the symmetrical curve shown results. In this position the two sides of the response curve are very nearly alike and the filter will thus afford the maximum over-all selectivity. However, under actual operating conditions, while several stations may cause some degree of interference, there is often one station which is so much stronger than the desired signal that even the selectivity provided by Fig. 26 is insufficient. When this is the case, the phasing control may be adjusted to provide maximum attenuation of the interfering wave.

An illustration, consider the case of a signal and two interfering waves as previously mentioned. If the 467 kc/s interference were so strong that the 3,000 cycle tone produced by it caused serious interference with the 1,000 cycle tone produced by the signal, the phasing control could be adjusted to produce maximum attenuation at 467 kc/s. The response curve would then be as shown in Fig. 27. Here the attenuation at 467 kc/s is so great that the interference caused by the 3,000 cycle beat note is no longer troublesome even though the interference it produced may be several thousand times as strong as the desired signal. While the attenuation at the audio image has been somewhat lessened, it is still over 40 times or 32 DB. By means of the phasing control, the area of the maximum attenuation may be shifted at will throughout a range of some five thousand cycles, on *either side* of the resonant frequency of the crystal itself.

THE PRACTICAL USE OF THE QUARTZ CRYSTAL AS A FREQUENCY CONTROLLING DEVICE.—The first crystal frequency control was merely a means of holding the frequency of a conventional oscillating circuit steady. The ordinary Armstrong circuit was used with the crystal connected between the grid and plate of the tube. It was found that in such a circuit the crystal tends to keep the frequency of the oscillator from swinging.

It is not necessary to discuss the entire history of the development of the crystal oscillating circuit. The first work of this sort was done by Cady. His circuits were oscillating circuits but were not intended to supply any great amount of power.

Dr. D. M. Miller, then at the Naval Research Laboratory in the City of Washington, brought out one of the first circuits in which the oscillations were really developed in and controlled entirely by the crystal. This circuit is shown in Fig. 28.

The crystal is placed on a heavy brass plate with a small brass plate resting on top of the crystal with a small flexible connecting wire. This method of mounting is used regardless of whether the thickness or longitudinal vibration is used. The top plate is connected directly to the grid and the lower plate is connected to the filament.

The operation is as follows: The switch is closed causing a rush of plate current from the filament to plate. With the grid situated between the filament and plate, the grid assumes a certain difference of potential with respect to the filament. Since the crystal is connected directly between the grid and filament, the difference of potential will be impressed across the crystal. The crystal possesses the "Piezo-Electric" properties previously described so that this difference of potential will cause the crystal to be compressed. As soon as the crystal has contracted, its elastic properties will cause it to swing back to normal and then momentum will cause it to expand. On the expansion a difference of potential will be developed by the crystal itself, having a polarity opposite to that of the original charge. This difference of potential impressed between grid and filament will cause a corresponding variation in plate current and therefore in the plate voltage. This is all that is necessary to develop power in the tuned plate circuit. The study of oscillator circuits shows that if power is developed in the plate circuit some of it will be transferred back through the grid to plate capacity of the tube.

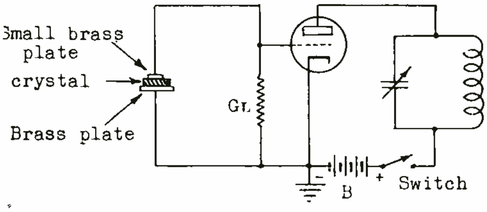


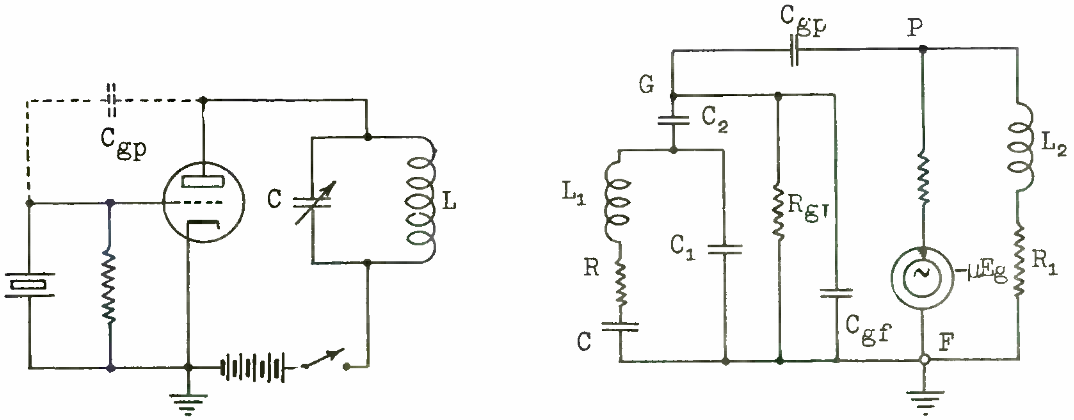
Fig. 28.—**Miller crystal oscillator circuit.**

The electrical and mechanical cycle has been developed in the crystal, the first impulse when the plate circuit was closed having caused the crystal to contract, return to normal, expand due to its momentum and return to normal again. If all the forces acting on the crystal were removed, the elasticity of the crystal would cause it to continue vibrating at its natural period, each vibration being weaker than the preceding one.

The action is very similar to that of a pendulum. When once a pendulum is started swinging, its movement can be continued with a very small amount of force *if the force is applied at the proper instant.* With the pendulum that force should be applied *just as the backswing commences.* This is also true for the crystal; the force should be applied just *after* the expansion has been completed and the crystal is beginning to return to normal. If power is applied at that instant a very small amount of power will maintain the crystal in a vibrating or oscillating condition.

To supply power to the crystal at the proper instant *the plate circuit must be inductive.* If it is desired, also, to develop considerable power, it is necessary to use a tuned plate tank circuit which, in order to have a large current flow, must be operated *near* resonance. Since the plate tank circuit is a parallel circuit, it would be resistive if tuned exactly to resonance with the natural period of the crystal and the crystal could not oscillate. In order that the plate circuit may act as an inductance at the natural frequency of the crystal it must be tuned to a *frequency slightly higher than that of the crystal.* This is very important because the crystal will not oscillate under any other condition. Thus, if it is desired to operate the crystal at a frequency of 600 kc/s, the plate circuit should be tuned to approximately 615 or 620 kc/s. Being tuned to a freq. higher than the crystal freq. it will act as an inductance, and being tuned so near resonance the circulating current will be large. *It should be thoroughly understood that the frequency of oscillation is affected only slightly by the tuning of the plate circuit.* If the plate circuit is further detuned the current in the circuit will be decreased, *but the frequency of this circulating current will be substantially that of the natural period of the crystal.* However, changes in circuit adjustments will have *some slight* effect on the frequency of oscillations and this effect must not be neglected if a very constant frequency is required.

It must be thoroughly understood that the primary function of the crystal oscillator in any device is to furnish a *constant* frequency. Every other function of the oscillator is subordinate to this duty. In some oscillators which are employed in broadcast transmitters, the oscillator is very lightly loaded and followed by an extra stage of amplification. The grid of the first amplifier is not driven positive to avoid loading of this nature. The frequency of oscillation is that for which the *total circuit reactance* is zero. In most practical crystal oscillator circuits, this is very nearly but not exactly the anti-resonant frequency of the crystal. There is always some slight frequency range over which the oscillator as a unit may drift, and in the case of the crystal oscillator, the sharpness of the resonance curve makes this possible frequency shift with a variation in circuit parameters very small. The shift may be relatively large or small depending on the parameter which is changed. The equivalent electrical circuit for the usual crystal oscillator is shown in Fig. 29. It is readily apparent that the circuit reactance



Grid Fil. Connection

Equivalent network

Fig. 29.—Equivalent circuit of crystal oscillator.

will be dependent on other factors than the crystal alone. However, it is the crystal circuit which largely determines the output frequency.

Examination of the equivalent circuit will show that the capacity of the grid to filament, C_{gf}, is shunted across the crystal. This capacitance is not the simple grid to filament capacity, the value for which is given in the tube manual, but is a complicated function of the tube and load. With some tubes, the effective C_{gf} is only slightly greater than the simple C_{gf} of the tube manual, with others it is many times this value. This increase in C_{gf} would not be serious if it were constant. It is mainly dependent on load impedance, grid to plate tube capacity and amplification factor. Whenever the plate output circuit is varied, the effective C_{gf} is varied. This changes the frequency by a small but never negligible amount. Also, because it is dependent on the tube's amplification factor, crystal oscillator tubes with high-μ values will have the greatest variation in tube input capacitance. It is also evident that tubes with large grid to plate capacitance will also suffer in this respect.

Other factors which affect the circuit parameters are variations in filament emission and variations in plate voltage. The first of these is not very serious but the second can cause trouble with maintainance of constant output frequency because a variation in plate voltage means a variation in plate resistance. If constant frequency is to be maintained, the plate supply voltage must be constant.

The proper tube for use with a crystal is thus a compromise. A high-μ tube is desirable because of ease of driving control; thus the crystal is not subjected to too great stresses. Unfortunately, such a tube in the triodes has a high grid to plate capacitance which means that excessive energy will be transferred from the plate to the grid. Pentodes, on the other hand, have high-μ values with small grid to plate capacities. Also, by proper choice of screen and plate supply, the stabilizing effect inherent in the electron coupled oscillator developed by Dow may be realized. This does not mean that triodes must not be used as crystal oscillator tubes; many excellent circuits employing triodes are used. But the triode does lack advantages which the pentode possesses.

In the adjustment of the oscillator, whether employing triode or pentode, there is also the factor of stable operation. Experience with such an oscillator quickly reveals that the output increases rapidly as one tunes the output circuit closer and closer to the anti-resonant frequency of the crystal. The plate current approaches some minimum value and suddenly oscillations cease, the output becomes zero and the plate current rises to some maximum value.

These conditions are illustrated in Fig. 30. In the vicinity of the discontinuity of plate current and tank current, the operation of the oscillator is unstable. For a given loading on the oscillator circuit, the plate current and the tank current values should be so chosen that stable operation and reliable starting of the oscillator are insured. The region labelled A shows approximately where unreliable operation may be expected for the plate current in that range, while the region of B is indicative of reliable starting and operation. Adjusting the operating point as shown has other advantages also. First, it sets the tank circuit at a point far enough from maximum output that excessive excitation voltage will not be supplied to the crystal as the driving adjustment to the first buffer is varied which results in a variation in loading and hence tank impedance. Second, it keeps the tank circuit far enough from maximum output that variations in other circuit parameters are not so liable to stop oscillations.

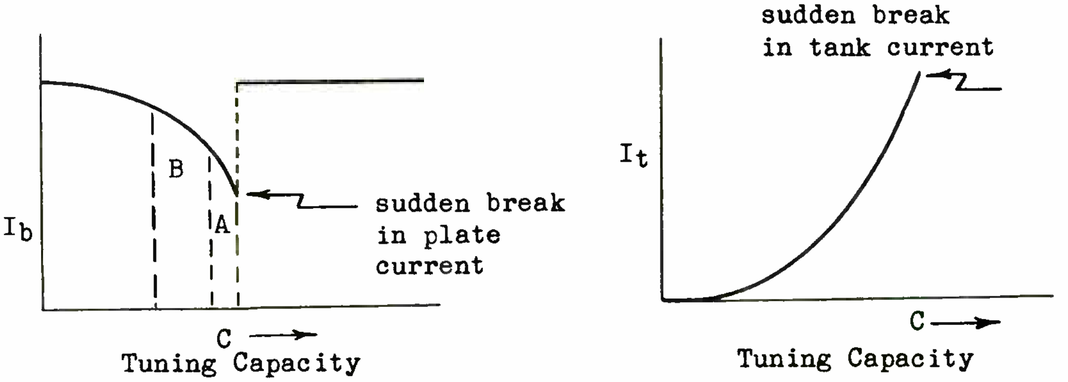


Fig. 30.—**Plate current and tank current variations in crystal oscillator circuit.**

Most modern oscillator circuits use a grid leak to furnish bias. This leak will vary from 5,000 ohms to possibly 100,000 ohms. For the lower values of bias resistor, it is recommended that a small r-f choke be placed in series with the grid leak. This will reduce the loading on the crystal where the grid leak is of a low order. It must be understood that the values given above are relative; that a considerable deviation from a given value is possible with but small effect on the operation.

The basic circuit for a triode tube in the crystal oscillator circuit is shown in Fig. 31. There may be small circuit refinements by a particular designer but fundamentally the circuit remains unchanged. For example, one manufacturer may use a 0 - 1 or 0 - 5 milliampere meter in series with the grid leak to indicate oscillations.

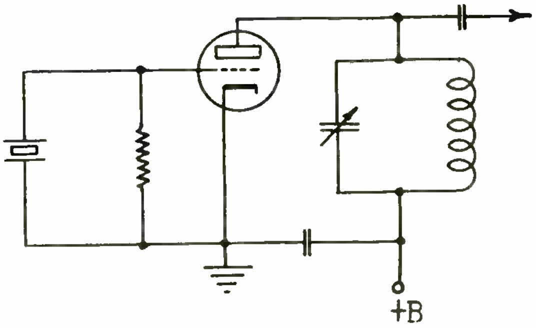


Fig. 31.—**Basic crystal oscillator circuit using a triode tube.**

One manufacturer may include a series r-f choke, etc. If one substitutes

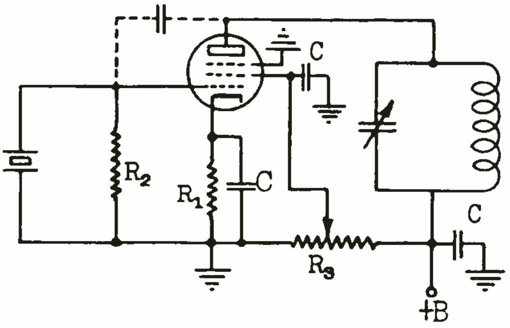


Fig. 32.—**Multi-element tube used as crystal oscillator.**

the pentode or tetrode tube for the triode, the circuit becomes that of Fig. 32. Observe that there is nothing added so far as the a-c operation is concerned. The circuit refinements consist of additional electrodes and d-c bias voltages for them. Both the triode and pentode (or tetrode) employ a tuned output circuit. However, this last is not strictly necessary unless one desires a greater output than is possible with a coil alone in the output circuit. The pentode tube will in general employ a smaller value of grid leak than the triode because of its proportionately greater μ value. The plate voltages to be used with a triode will run from values as low as 150 volts to values in the neighborhood of 350 volts with the upper end perhaps as high as 500 volts. These higher values are not recommended because of the excessive strain on the crystal because of increased feed-back energy. The voltages employed will be based on the manufacturer's ratings for the tube used. For the pentode, the plate voltage will run around 350 volts and the screen voltage around 100 volts with a maximum of 130 volts. For the tetrode tubes, plate voltages of 350 to 400 volts are satisfactory, with the screen grid voltage at 250 volts. Suppressor grids should be grounded. In some very well-shielded pentode types, it may be necessary to supplement the exceptionally low grid to plate capacity with an external capacity of from .5 $\mu\mu$f to a value not greater than 2 $\mu\mu$f. This is shown in Fig. 32 by the dotted lines. By-pass capacitors shown are not critical, values of from .01 μf to .001 μf are usual. The screen grid in both tetrodes and pentodes should be grounded through a capacitor to maintain them at as nearly r-f ground potential as possible. The capacitors should be located as near to the screen grid terminals on the socket as practical and should run directly to ground with the shortest possible leads. In Fig. 32 there is shown a cathode resistor and shunting capacitor. This resistor may be in the order of 300 ohms and is not strictly necessary in any but the beam tetrode types. It is always advantageous in any oscillator because it aids in limiting the plate current when the grid bias ceases due to cessation of oscillation by the crystal.

Tubes which may be employed for crystal oscillators are the receiving type triodes and pentodes or the lower powered triodes, pentodes and beam type tetrodes. Some of the favored types are the 210, 6C5, 6F6, 47, 205D, 247A, 802, 807, 814, and 843. The cathodes may be either directly or indirectly heated and a-c may and usually is employed for filament heating.

Modern crystal oscillators employ the tank circuit in the plate circuit. The r-f component of plate voltage is developed across this tank and the voltage fed back to the crystal through the grid to plate capacity is always proportional to the tank voltage. As the crystal oscillator is loaded by the buffer amplifier grid, the tank impedance decreases and the r-f voltage developed decreases. So it is seen that the driving voltage of the crystal also decreases as the loading is increased. This is not a desirable situation. It would be better if the driving voltage of the crystal increased as the loading increased rather than decrease. Ultimately, the loading will decrease the tank impedance to the point where the voltage across it will fall to a value whereby the crystal will be insufficiently excited and oscillations will cease when they are needed most. It is a fact that the crystal is receiving the greatest excitation when the oscillator tank is unloaded and the least when it is loaded. It makes no difference whether the tank circuit is in the plate lead as shown in Figs. 31 and 29 or in the cathode lead as shown in Fig. 33. It would appear that an oscillator circuit wherein the excitation to the crystal increased with loading would be desirable. Such circuits have been devised and appear under various names such as the Tri-Tet and others, to be discussed later in this assignment.

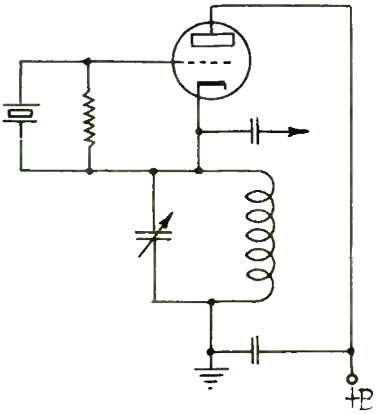


Fig. 33.—Tank circuit shown in cathode circuit.

The problem of obtaining relatively large outputs of power from a crystal oscillator circuit presents difficulties. In general, when the oscillator is required to furnish considerable power, the frequency stability suffers directly with the power requirements, particularly when only triodes are available. Today, with modern beam tubes and high sensitivity pentodes available, the difficulties are much less.

However, where a certain power output is necessary with a minimum number of tubes, the solution is not easy. The following discussion will indicate the steps in the process which a large user of crystal controlled transmitting equipment employed in its solution. The principal tube available was a triode, Type 210. The fundamental oscillator circuit of Fig. 28 was employed and research on this circuit was undertaken.

The grid leak is used to furnish a return to the filament to prevent the tube from blocking, because the crystal itself is an insulator. This was the weak point in the original circuit with the tubes that were available and prevented the development of any great amount of power in the circuit with triode tubes. Too large a proportion of the small amount of power supplied by the crystal was dissipated in the grid leak.

The next and very important

change in the circuit was the removal of the grid leak and the substitution of a radio frequency choke and negative bias voltage. This is shown in Fig. 34. The "C" battery places a negative bias on the grid of such value as to entirely prohibit the flow of grid current. The radio frequency choke performs its usual function of preventing the leakage of radio frequency current and keeping all of the power developed by the crystal on the grid of the tube.

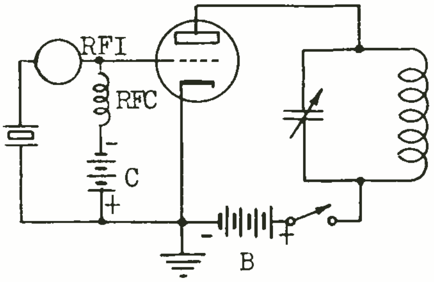


Fig. 34.—**Battery bias for oscillator tube.**

This combination of radio frequency choke and negative biasing voltage increases the efficiency of the tube and circuit many times. In fact, the same tube that is unable to develop as much as one watt when using the grid leak is able to develop almost twenty watts when using the choke and fixed negative bias. This made it possible to use a 7.5 watt tube to drive a 250 watt amplifier tube, although, in modern practice such a large power output and high tube step-up factor are seldom used.

To develop this much power from a Type 210 tube it is necessary to have all adjustments such that the tube is operated at maximum efficiency with as high as 750 volts on the plate and negative bias of about 60 volts. This is not considered good engineering practice.

It was later found somewhat more practical to use a 50 watt tube in the crystal circuit and then work the tube at comparatively low efficiency. It is much easier to obtain 25 watts from a crystal controlled 50 watt tube than to obtain 15 watts from a 7.5 watt tube. In fact, the 50 watt tube can be operated with a radio frequency choke without the use of a biasing battery and will still deliver sufficient power, with a plate voltage of only 400 or 500 volts, to drive the grid of a 250 watt amplifier tube.

Power pentodes, such as the Type 802 and the beam power tube Type 807, are particularly adaptable for use as crystal controlled oscillators because of their power sensitivity. When such high gain tubes requiring small excitation voltage for full power output are used, excessively strong crystal vibrations are not required for good power output. As a comparison with a low μ triode: Operated as an oscillator, the Type 203-A triode requires approximately 5 watts of driving power for output of 65 watts. The Type 807 beam power amplifier operated in the same manner requires only approximately .22 watt driving power for output of 37.5 watts. The latter has a *much* higher power sensitivity and will correspondingly offer a much lighter load to the crystal for given power output.

The crystal current should never exceed the value specified by the manufacturer. No definite values of crystal current can be given with the many types of cuts available. The crystal current is the actual r-f current through the crystal and can be measured by its heating effect. This may be done either with a small lamp, such as a flash light bulb or, preferably, by an r-f milliameter. This current must not be allowed to become too great as it is the current which heats the crystal and causes violent vibration which may shatter it. Excessive crystal current means excessive feed-back voltage and crystal current is a ready means of determining when this condition is obtained. For X cut crystals, a figure of 120 ma maximum r-f current has been used. Here again no definite value can be stated for all crystals and operating frequencies. The commonly encountered reasons for excessive crystal current may be enumerated as follows: Plate supply voltage excessively high, control grid bias excessive, improperly by-passed screen grid circuit, stray feed-back due to poor shielding or placement of parts, feed-back due to oscillations in the buffer stage following the crystal.

Fig. 35 illustrates a practical crystal oscillator followed by a stage of radio frequency amplification. This diagram shows the adjustments, meters, and other apparatus necessary for the proper operation of the circuit.

The filaments of both tubes are heated with a.c. Since the amplifier tube is usually a larger tube than the oscillator and requires a different filament voltage, a separate filament transformer is used for each tube. This could be accomplished by using a single tapped transformer.

A separate plate voltage supply is used for each tube. There are several reasons for this. First,

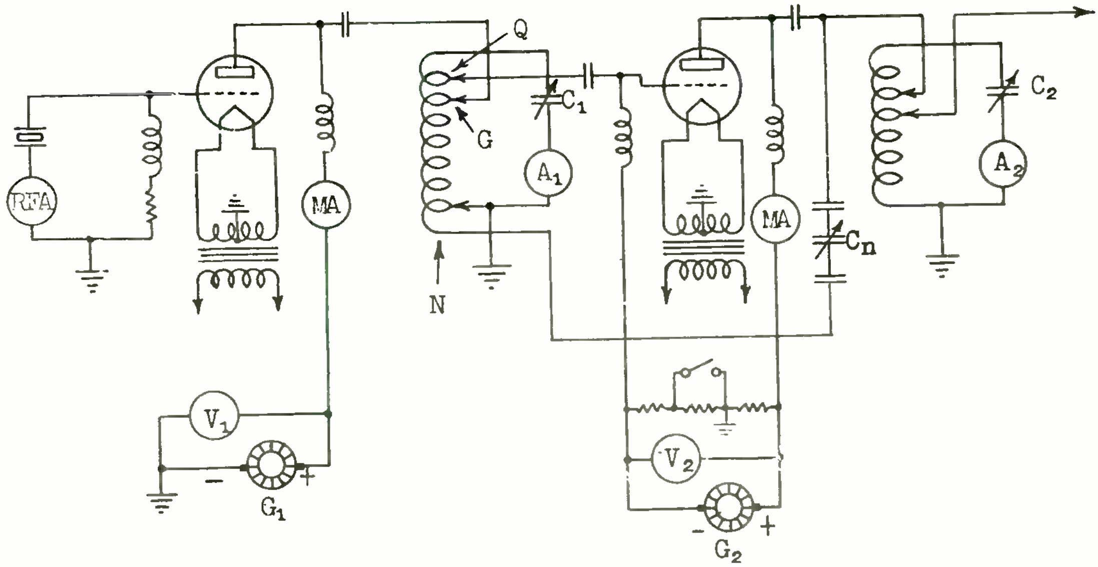


Fig. 35.—Crystal oscillator followed by an amplifier stage.

the crystal controlled tube requires a lower plate voltage than does the amplifier tube; usually about 450 volts for the oscillator and about 1,500 volts for the amplifier, assuming a 50 or 100 watt amplifier. Second, a grid bias keying system is used and the operating bias for the amplifier is obtained by means of an IR drop across a portion of the resistance across the plate generator.

It will be seen that *only the amplifier circuit is keyed.* This is one of the peculiarities of a crystal controlled circuit. When the plate circuit of the oscillator is closed an appreciable time is required for oscillations to build up. If that circuit is keyed the oscillations may not build up as rapidly as the key is opened and closed. The crystal circuit is oscillating during the entire time the transmitter is being used, whether the key is open or closed.

The Rice neutralizing circuit is used to prevent oscillations in the amplifier circuit. The neutralizing circuit is not used if the amplifier is used as a frequency doubler, or if a screen grid amplifier tube is used.

To adjust the transmitter, first turn on the filaments and then start up the crystal plate generator, G_1. Place Tap G on the coil several turns above ground and vary capacitor C_1 over its scale. If the coil taps on this circuit are properly adjusted, at some point on the dial the crystal should start oscillating. This point will be at a frequency adjustment somewhat higher than the resonant frequency of the crystal, and will be indicated on the capacitor dial as a *lower* dial reading than would be the case if the circuit were adjusted to the resonant frequency of the crystal.

When the crystal starts to oscillate, the condition will be indicated by current readings in the radio frequency milliammeter in series with the crystal and in radio frequency ammeter A_1 in the plate tank circuit. If the oscillator grid bias is obtained by means of a grid leak, oscillations will also be indicated by a decrease in the oscillator plate current. If a battery bias is used and the tube is biased below the lower bend of the $E_g I_p$ curve, oscillations will be indicated by an increase of plate current. It will now be necessary to adjust the circuit so as to obtain the most efficient operation. The plate current should be fairly low and the plate of the tube should operate cool; the crystal current must be kept below whatever maximum value has been found to be safe for the particular crystal; the current in the tuned circuit should be as high as possible consistent with stable oscillations and a sufficiently low crystal current. The most important adjustment in obtaining this condition is the adjustment of plate Tap G. To increase the crystal current, increase the number of turns between this tap and ground; to *decrease* the crystal current, *decrease* the number of turns between the plate tap and ground. This adjustment is important because if the plate tap, and consequently the crystal current, are too high, the crystal will probably be cracked. When starting the adjustments the plate tap should be placed very low as a precautionary measure. If, with this adjustment, it is difficult to keep the crystal current and plate current sufficiently low, the plate voltage should be reduced.

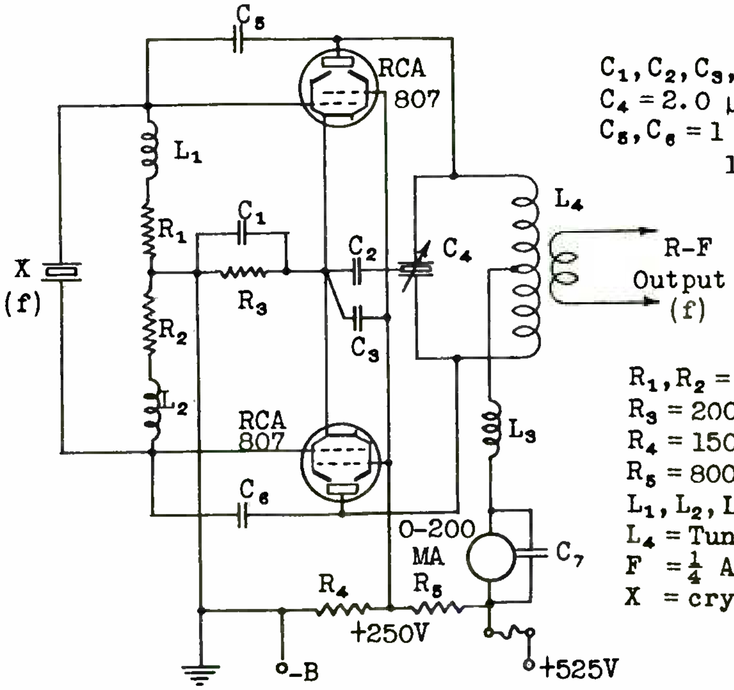
When using a 7.5 watt oscillator (Type 210 tube), a biasing voltage of from 40 to 60 volts should be used in the crystal circuit and a plate voltage of from 350 to 500 volts should prove satisfactory although as high as 650 volts may be used at the lower frequencies. Under these conditions from 3.5 to 4.5 amperes should be obtained in the plate tank circuit.

When using a 50 watt oscillator with low plate voltage no biasing voltage will usually be required; the plate voltage should be from 450 to 500 volts. The current in the tuned tank circuit may be between 5 and 7 amperes. A grid leak may be used to furnish a bias and reduce the plate current.

When the crystal circuit adjustments are completed, excitation tap Q and neutralizing tap N should be placed on the coil. The plate voltage of the amplifier should be adjusted to about one-half the normal voltage. Adjust the output circuit of the amplifier tube to what is thought to be approximately the correct number of turns. Then close the key and adjust capacitor C_2 to obtain the maximum current in this circuit.

The amplifier should next be neutralized. Then adjust the amplifier circuit for maximum efficiency and greatest output. These adjustments have been described in detail in preceding assignments. When this is completed and it is certain that the neutralizing adjustment is correct, the plate voltage may be increased to the normal operating value for the tube used. The antenna circuit, or next amplifier stage, is then adjusted and necessary minor changes are made in the buffer circuits.

Fig. 36 shows a push-pull crys-



C_1, C_2, C_3, C_7 = 0.005 μf, mica
C_4 = 2.0 μμf/meter/section
C_5, C_6 = 1 to 2 μμf (not larger) 1000 V.

Power Output 30 watts

R_1, R_2 = 50000 ohms, 1 watt
R_3 = 200 ohms, 20 watts
R_4 = 15000 ohms, 10 watts
R_5 = 8000 ohms, 25 watts
L_1, L_2, L_3 = R-F choke
L_4 = Tune to crystal frequency
F = $\frac{1}{4}$ A. high-voltage fuse
X = crystal, frequency "f"

Fig. 36.—Push-Pull oscillator circuit.

tal oscillator employing two Type 807 beam tubes. As stated, this oscillator has an output of approximately 30 watts which may be used to drive a quite large succeeding amplifier stage. In this case a combination of self-bias (by means of cathode resistor R_3) and grid leak (R_1 and R_2) is used. With high gain tubes this allows the development of large power output without overworking the crystal. Feed-back is obtained through capacitors C_5 and C_6.

MAINTAINING CONSTANT CRYSTAL TEMPERATURE.—The most practical method of operating the crystal at a constant temperature is to enclose it within a temperature insulated compartment, the temperature of which is maintained considerably higher than the maximum room temperature. 50° Centigrade is usually considered satisfactory except in tropical countries where a somewhat higher operating temperature may be necessary. The compartment may be double, the crystal holder being enclosed within the inner compartment and the electric heater in the outer compartment. In this way, after the inner compartment has reached the optimum temperature, its temperature, due to the additional insulation, will not fluctuate with slight temperature variations in the outer compartment.

The thermostat should be placed in the outer compartment, where double compartments are used, in order that it may respond to temperature variations at once before those variations can affect the temperature of the inner crystal compartment. The thermostat has an element which expands and contracts with increases and decreases of temperature. It is adjusted so that at temperatures above an optimum value the contacts close, opening as soon as the temperature falls below the value for which it is adjusted (or it may be designed to operate in just the opposite manner). The opening and closing of the thermostat contacts control a relay which, in turn, opens or closes the heater circuit as the temperature exceeds or falls below the desired value.

Fig. 37 shows a high quality temperature control box in which provision is made for mounting two crystals, either of which may be connected into the circuit by means of a switch on the panel. The temperature controlled space is made up of walls consisting of interleaved heaters and distributing and insulating layers formed of aluminum and balsa wood respectively. The temperature in the crystal compartment is maintained constant within ±0.1° C for external temperature variations of ±16° C. The unit is ordinarily supplied with a fixed mercury type thermostat which operates at 50° C. A thermometer graduated in 0.5° C divisions from 40° to 60° C is mounted behind a slot on the panel and indicates the tempera-

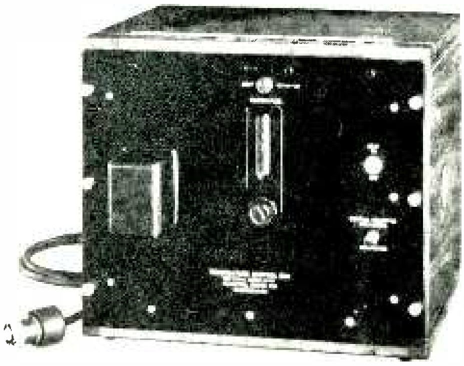


Fig. 37.—Temperature controlled box for crystal oscillator circuits.

ture of the inner compartment.

There are two commonly used types of thermostats, the bimetallic thermostat and the mercury thermostat. The operations of a mercury thermostat are similar to that of an ordinary thermometer, the rising and falling mercury simply closing and opening an electrical contact as the temperature varies. The bimetallic thermostat consists of a spiral formed of two dissimilar metals. That is, two metals having different temperature coefficients are made in the form of thin narrow strips and welded together, then coiled in the form of a spiral shaped spring, one end being permanently secured to the base of the thermostat. This is shown in Fig. 38. The metal having the highest temperature coefficient of expansion is on the inside. As the temperature is increased the difference in expansion tends to uncoil the spiral breaking the electrical contact. As the temperature is decreased the contact again closes. Thus, the two types of thermostats normally produce the opposite result, the bimetallic type closing the relay circuit when the temperature decreases and opening the circuit when the temperature increases above a predetermined value; the mercury thermostat closes the circuit with a temperature increase.

When used in a crystal temperature control unit, it is essential that the thermostat be sensitive to small temperature variations in the order of a fractional part of a degree because a single degree of temperature variation will cause a considerable crystal frequency variation. With such a sensitive device it is impractical to pass the heater current through the thermostat contacts. Therefore, the thermostat itself is used to actuate a relay which in turn opens and closes the heater circuit. For this purpose both the mercury and the bimetallic thermostats have advantages and disadvantages. The principal advantage of the bimetallic type is

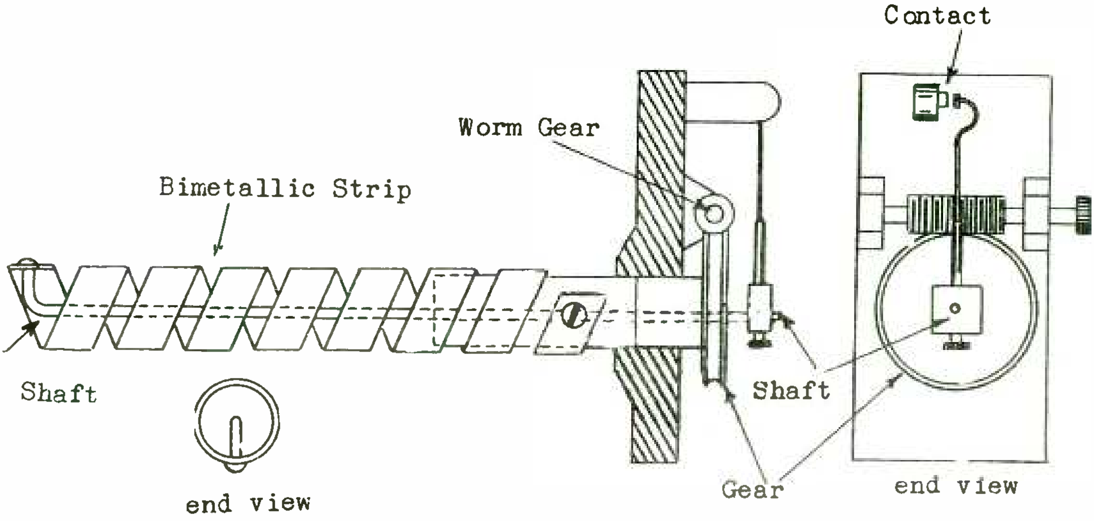


Fig. 38.—Bimetallic thermostat construction.

its ruggedness. On the other hand, this type is not nearly so sensitive as the mercury thermostat. The mercury thermostat is much more sensitive and accurate but it must be used only to break circuits carrying very small currents. The controlling factor on the useful life of a mercury thermostat is the current passing through it. If the current is not allowed to exceed eight or ten mils the life will be excellent.

The thermostat may be used in two ways to control a relay—either in series with the relay and battery or across the relay windings. Fig. 39 shows the series circuit; Fig. 40 shows the parallel arrangement. These assume the use of mercury thermostats. In Fig. 39 the thermostat is in series with the relay winding. As it closes with a temperature increase above the predetermined value, the relay is energized, causing it to open, in turn opening the heater circuit and allowing the compartment temperature to fall off to normal. As the temperature decreases below the desired value the thermostat contacts open, deenergizing the relay and closing the heater circuit. With this circuit a fairly high resistance relay must be used to limit the current through the thermostat. If, with a 6 volt battery, the current must not exceed 10 mils, the relay resistance must not be less than 6/.01 or 600 ohms.

In Fig. 40, the parallel connection of the thermostat operates to short circuit the relay winding when the temperature increases. Thus, the relay operation must be reversed. A decrease of temperature opens the thermostat contacts, removing the short-circuit from the relay winding, energizes the relay and causes the relay contacts to close the heater circuit. The value of R_2 is calculated from the relay current requirements and the resistance of the relay. If the relay requires 15 mils and a 6 volt battery is used, then the total circuit re-

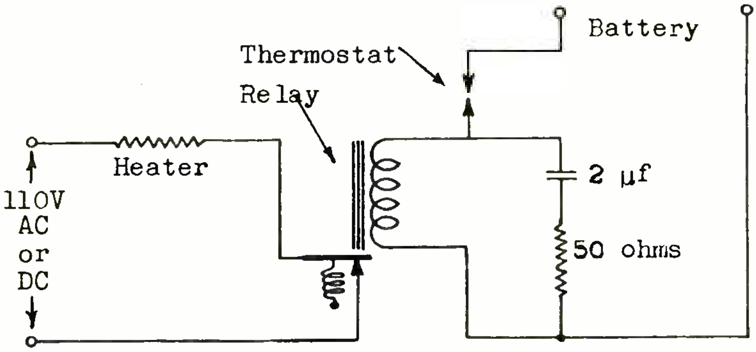


Fig. 39.— Series circuit for thermostatic relay.

sistance must be, $R_1 + R_2 = 6/.015$ or 400 ohms. If the relay resistance is 150 ohms, then $R_2 = 400 - 150$ ohms or 250 ohms. The first objection to this circuit is the fact that the current through the thermostat is greater than the relay current and the collapse of the field around the relay winding tends to produce a spark at the thermostat contacts. This objection does not apply to the circuit in Fig. 39. The second objection to the circuit of Fig. 40 is the fact that if the battery voltage drops to too low a value the relay current may become too small to close the heater circuit. This is particularly true due to the large value of series resistance. However, both circuits are giving excellent results in actual installations.

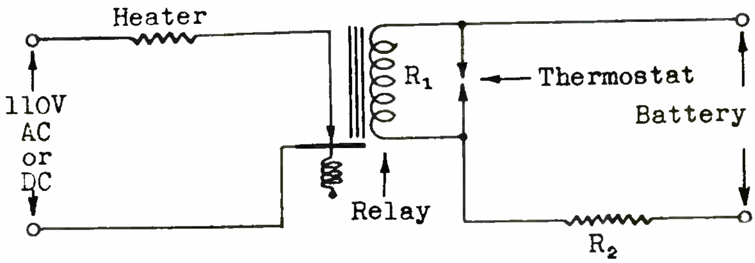


Fig. 40.—**Parallel circuit for thermostatic relay.**

Thermostats are often used in conjunction with a vacuum tube relay to short in or out resistance, thus, changing the grid bias on a vacuum tube, this change of bias in turn controlling the tube plate current which in turn operates a relay. With such an arrangement the thermostat current can be kept extremely low and positive instantaneous action obtained through the use of the vacuum tube relay.

The crystal constant temperature compartment should contain a good thermometer so that the operation of the thermostat and relay circuit may be frequently checked to see that the proper crystal temperature is actually maintained. Most modern transmitter installations include duplex crystals with individual constant temperature compartments so that a failure of one unit will not put the transmitter out of commission. When a duplex crystal installation is provided the crystals are usually alternated in operation daily.

With the advent of the low TC crystals, the need for elaborate temperature controlling ovens has been very materially reduced. This has greatly decreased the current requirements for such transmitters on aircraft where the power drain for a constant temperature compartment must be considered. The Federal Communications Commission's requirement of temperature constancy for the special low TC cuts is 1° C as compared with .1° C for other types of cuts. This also requires a much less elaborate thermostat. The entire cost and size is thus reduced. Bulky ovens have been replaced by much smaller units. A modern low TC crystal oven is shown in Fig. 41.

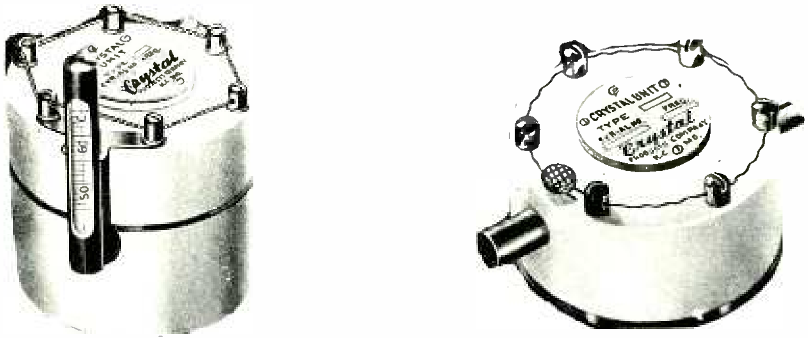


Fig. 41.—**Modern low temperature control oven.**

In conjunction with crystal oscillators for broadcast transmission the Federal Communication Commission requires the use of an approved type of frequency monitor having a *visual* indication of frequency variation. This monitor includes a crystal accurately ground to a given frequency difference with the required transmitter frequency. Several companies manufacturing such monitors use a 500 cycle difference, although, any desired low frequency may be used. The beat note produced by the output of the crystal monitor and the output of the crystal controlled transmitter is amplified until it is of sufficient magnitude to operate a frequency indicating device. The design of the frequency meter is such that the specified beat frequency falls on the center of the scale which is marked "Zero." From that point the frequency, plus or minus on each side of the "Zero" setting is calibrated in cycles. Thus, when the transmitter frequency deviates for any reason causing a change in the monitor beat note, the direction of deviation as well as the magnitude of the deviation in cycles is indicated.

By the use of a carefully designed crystal control master oscillator and an accurately calibrated monitor with a visual indication of frequency deviation, the frequency of the transmitter should easily be kept within a small portion of the plus or minus 20 cycles deviation allowed by the FCC regardless of variation in room temperature, line voltage variations, and other disturbing factors. In many broadcast transmitter installations the frequency is held consistently within less than 10 cycles deviation and in some installations the deviation is usually not more than one or two cycles.

THE TRI-TET CIRCUIT.—The theory of operation of the Tri-tet type of oscillator may be briefly explained as follows. The basic circuit is shown in Fig. 42. It will be observed that there are tuned circuits in both the cathode and the plate circuits. For all around operation a well-screened type of tube is preferable, such as the 802 pentode.

The excitation for the crystal oscillator is obtained from the tuned circuit in the cathode circuit. The crystal, cathode tuned circuit, screen grid circuit and control grid circuit resembles Fig. 32 except for the tuned cathode circuit. The r-f component in the screen cathode circuit provides the excitation for the crystal. With the plate circuit present, the r-f component in this circuit must also flow through the tuned circuit already in the cathode. With this plate circuit unloaded, the impedance presented is high and the r-f component is correspondingly low. The excitation voltage to the crystal is thus seen to be a function of two currents, the r-f component due to the screen circuit (which remains essentially constant) and the r-f component due the plate circuit. The latter current will vary with the loading, increasing with an increase in load. As this component increases, it increases the voltage across the cathode tuned circuit and consequently increases the excitation voltage to the crystal. Thus, this circuit operates to increase the excitation to the crystal as the load increases. The most important requirement of this type of circuit is to employ the proper type of cathode circuit. It should be tuned so as to be inductively reactive and have a low resonant impedance. This means large C and low L, in contrast with the usual values of L and C for crystal oscillator tanks. In no case should it be tuned to crystal frequency of harmonic resonance. The proper criterion of behavior is reasonable r-f crystal current, because the crystal current is a measure of the r-f excitation voltage.

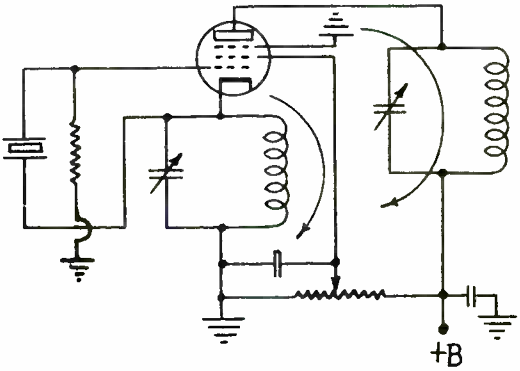


Fig. 42.—Tri-Tet circuit for crystal oscillators.

The Tri-tet circuit is also well adapted for frequency multiplying. The cathode circuit is unchanged. A tuned circuit is inserted in the screen circuit and tuned to the fundamental of the crystal. The tuned circuit in the plate circuit is then replaced with a circuit which is resonant to the harmonic of the fundamental desired. The circuit is illustrated in Fig. 43.

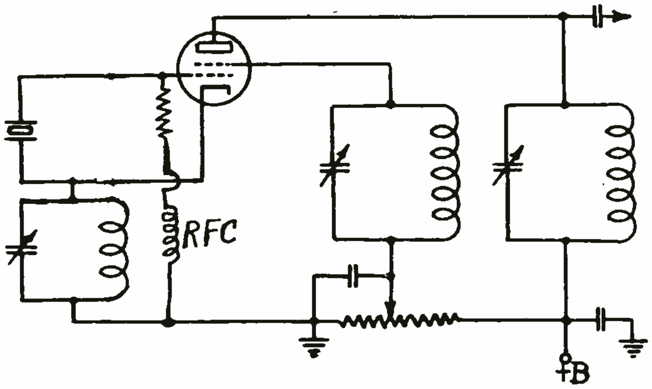


Fig. 43.—Tri-Tet circuit for frequency multiplying.

THE PIERCE OSCILLATOR.—The basic circuit for this type of oscillator is shown in Fig. 44. This is one of the earliest circuits employed with the quartz crystal. The plate circuit may be tuned but the possible advantage is academic. Ordinarily a choke alone is employed across which the r-f voltage is developed. The plate circuit must be capacitively reactive for oscillation and additional capacity to that already present in the form of the grid to cathode will normally be required to provide sufficient regeneration. This is the capacity C_1 and may be determined by experiment. The value will probably be in the order of 100 μμf. If a cathode resistor is employed, it may be about 1,000 ohms or so by-passed with the usual r-f by-pass capacitor. The Pierce oscillator has the advantages of simplicity and lack of tuning controls but has the disadvantage of relatively low output. The voltage that can be applied to the plate is limited by the voltage which the crystal can withstand with respect to r.f. Since the r-f voltage is a function of the d-c voltage, this limitation is evident. Any Pierce oscillator will require an extra amplifier stage. It is well adapted to oscillators employed in frequency standards and has found some application to commercial transmitters.

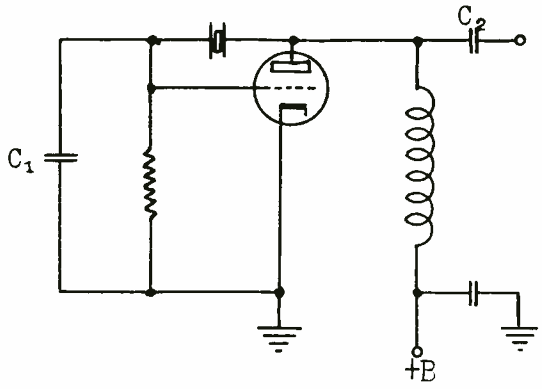


Fig. 44.—Pierce oscillator circuits.

CRYSTAL CALIBRATORS.—There are several types of so-called "Crystal Calibrators", all of which have a circuit similar to that illustrated in Fig. 45. It will be observed that the 100 kc/s crystal has an untuned plate circuit while the plate circuit for the 1,000 kc/s crystal is tuned. The output of the 100 kc/s crystal will have harmonics at all integral multiples of the fundamental frequency of 100 kc/s. That is, there will be frequencies appearing in the output of 100, 200, 300, 400, 500, and so on. The strength of the harmonics will be progressively weaker but with proper apparatus for their detection, such as a receiver, harmonics up to the one-hundreth or higher may be identified. The 100th harmonic of 100 kc/s is 100 × 100 or 10,000 kc/s. The 1,000 kc crystal will also have harmonics of integral multiples of 1,000 kc, appearing at 1,000 2,000 3,000, and so on. It will be observed that the tuned circuit for the 1,000 kc/s crystal uses a very large inductance and a relatively small capacity. This is to provide a circuit which will offer not only a large impedance to the fundamental but also to the harmonics. The frequency spectrum in every-day use will not require as high an order of harmonic from the 1,000 kc/s crystal as for the 100 kc/s crystal which makes use of an inductance only, thus insuring a relatively high impedance for all frequencies even if at the expense of output.

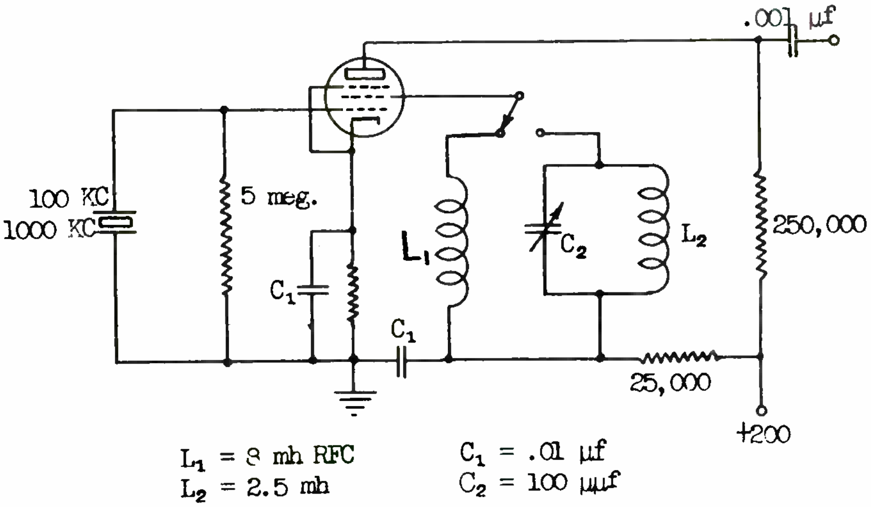


Fig. 45.—Crystal Calibrator circuit.

The crystal calibrator is useful in "calibrating" such devices as receivers, frequency meters, and the like. The procedure for use in calibration work is as follows: The particular harmonic of the calibrator is identified by a device, such as a signal generator or calibrated receiver, the accuracy of which need be only reasonable. The error between the actual and the correct reading is then determined. Suppose a receiver dial set at 1,410 kc/s is receiving a zero-beat signal from the crystal calibrator. Unless the receiver calibration is very far off, the correct value is evidently 1,400 kc/s and the receiver is indicating 10 kc/s too high for that setting. In another case, if one wishes to determine the proper setting of a signal generator for say 920 kc/s, the receiver is set to receive the 9th harmonic of the 100 kc/s crystal and this signal is then zero beat with the 900 kc/s output of the signal generator. The reading on the signal generator dial is then noted. Say this value is 453. The receiver is then tuned to 1,000 kc/s and set to zero beat with the 10th harmonic of the 100 kc/s crystal output or the fundamental of the 1,000 kc/s crystal. The signal generator is then tuned to zero beat at 1,000 kc/s and the dial setting again noted. The value of dial setting is 475. The proper setting of the signal generator dial may then be found by interpolation.

F	S
900 kc	453°
1,000 kc	475°

$$\Delta F = 1{,}000 - 900 = 100 \text{ kc}$$
$$\Delta S = 475 - 453 = 22^\circ$$
$$\frac{\Delta S}{\Delta F} = \frac{22}{100} \text{ degrees/kc}$$

Since 920 kc is 20 kc greater than 900 kc the dial setting for 900 kc must be increased

$$20 \times \frac{22}{100} = 4.4^\circ \text{ to obtain}$$

setting for 920 kc.

Setting for 920 kc = 453 + 4.4 =

$$457.4^\circ$$

The procedure may be reversed to find the frequency for a given setting of the frequency meter. For example, find the frequency corresponding to a setting of 460°. From the preceding data

$$\Delta F = 100 \text{ kc}$$
$$\Delta S = 22^\circ$$
$$\frac{\Delta F}{\Delta S} = \frac{100}{22} \text{ kc/degree}$$

460° is 7° greater than 453° so 900 kc must be increased by an amount equal to

$$7 \times \frac{100}{22} = 31.8 \text{ kc}$$

Thus a setting of 460° corresponds to a frequency of 900 + 31.8 = 931.8 kc.

CRYSTAL CONTROL OF RADIO FREQUENCIES

EXAMINATION

1. Why is quartz superior to other substances for the control of radio frequencies? What other substances develop marked piezo-electric effects and what are the disadvantages of those substances for use in radio frequency control?

2. Discuss the three axes of a crystal. Explain how an X cut crystal is cut with respect to the three crystal axes.

3. What is the advantage of a choke and biasing battery over the grid leak for supplying the operating bias for the crystal oscillator?

4. Explain the procedure for tuning up a crystal oscillator and triode amplifier to operate at the fundamental frequency of the crystal. Illustrate your explanation by sketching the circuit.

5. Explain the care to be taken in handling a crystal.

6. Describe the operation of two types of thermostats listing advantages and disadvantages of each. Sketch a circuit showing how a thermostat may be used to control the temperature of a crystal oven. Explain how the circuit operates.

7. The micrometer measurements on an unmarked quartz crystal are found to be: thickness 78.74 mils and length 1959.5 mils. The width is 1181.1 mils.

(a) What is the thickness frequency if the crystal is X cut?

(b) What is the thickness frequency if the crystal is Y cut?

(c) If the crystal is Y cut what is the approximate X axis frequency?

(d) If the crystal is X cut and is found to oscillate at 54.6 KC/s what is the Z axis dimension?

8. You are ordering a 550 KC crystal and oven for operation in the tropics. The highest temperature recorded at your station is 110° Fahrenheit. At what temperature would you request the crystal to be calibrated? Why?

8. *(Continued)*

9. You have an X cut crystal operating at 1430 KC/s in a 50° Centigrade oven. Between what temperature limits must the oven be held to keep the crystal within the allowable 20 cycle deviation limit?

10. A station has an assigned frequency of 9.5 MC/s which is obtained from a 2375 KC/s crystal by frequency doubling. The transmitter employs an X cut crystal calibrated at 50° C. The temperature coefficient of the crystal is -20 cycles/megacycle/degree. If the crystal temperature varies between 45° and 55° Centigrade over what range will the transmitter frequency vary?