CHAPTER XVII

Low-Frequency Quartz-Crystal Cuts Having Low Temperature Coefficients

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17.1 INTRODUCTION

MOST of the effort spent in developing quartz crystal orientations has been directed towards obtaining high-frequency crystals with advantageous frequency spectra and low temperature coefficients. Another important frequency region for which little work has been done is in the frequency region from 4 to 100 kc. This range is particularly important for carrier cable and open-wire communication work, since all of the oscillators and filters required are in this frequency region. In addition, a number of constant-frequency sources for use in controlling rotating machinery and time standards are desired. Another use to which the low-frequency crystal described here has been put is in controlling the mean frequency of the Western Electric frequency-modulated radio transmitter.[1]

It is the purpose of this paper to describe two new crystal cuts, the *MT* and *NT*, which cover this frequency range. The *MT* crystal is a longitudinally vibrating crystal, having a low temperature coefficient which can be used in the frequency range from 50 to 100 kc. The *NT* crystal is a flexually vibrating crystal having a low temperature coefficient, which can be used in the frequency range from 4 to 50 kc. Hence, by the use of these two crystals, this low-frequency range of from 4 to 100 kc can be covered adequately.

17.2 PROPERTIES OF +5-DEGREE *X*-CUT CRYSTAL VIBRATING IN LONGITUDINAL AND FLEXURAL MOTION

Both the *MT* and *NT* crystals are related to the +5-degree *X*-cut crystal used, respectively, in longitudinal and flexural motion. This crystal itself has been used as a longitudinal and flexural crystal to cover this frequency range. It therefore appears worth while to describe its properties and mode of operation.

The +5° *X*-cut crystal is cut with its major surfaces normal to the *X* or electrical axis of the crystal and with its length at an angle of +5° from the *Y* or mechanical axis. In terms of the recently defined I.R.E. system of specifying orientation angles, $\phi = 0$, $\theta = 90$ degrees, $\Psi = 85$ degrees. As shown by Fig. 17.1, the I.R.E. method of orienting a crystal consists in

[1] "A New Broadast-transmitter Circuit Design for Frequency Modulation," J. F. Morrison, *Proc. I.R.E.*, Vol. 28, Oct., 1940, pp. 444–449.

taking the X' axis along the length of the crystal, the Y' axis along the width of the crystal, and the Z' axis along the thickness dimension of the crystal. θ is then the angle between the Z and Z' axis, ϕ the angle between the $+X$ axis and the intersection of the plane containing the Z and Z' axes with the XY plane, while Ψ the skew angle is the angle between the length X' and the tangent of the great circle containing the Z and Z' axes. All angles are called positive when measured in a counterclockwise direction. Fig. 17.1 is applicable to a right-hand crystal (crystallographer's definition) and the positive X axis is the axis for which a positive charge develops on an extensional stress.

A long thin $+5°$ X-cut crystal is the member of the X-cut family which has the lowest temperature coefficient of frequency. This is shown by

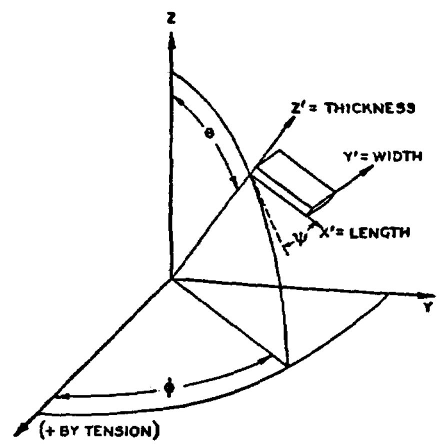

Fig. 17.1—I.R.E. system of designating orientations

Fig. 17.2 which plots the measured temperature coefficient of a number of rotated X-cut crystals. The $+5°$ crystal has nearly a zero coefficient while all other angles have negative coefficients. The modes of motion of a $+5°$ X-cut crystal are very similar to those of a 0-degree X-cut crystal which have been discussed at some length previously.[2] When the crystal is long and thin, the longitudinal expansion is the predominant motion. As the crystal becomes wider, a coupling to a face shear mode of motion becomes more prominent. This is shown by the fact that the resonant frequency is lowered and the nodal line is no longer normal to the length of the crystal. The face shear mode is closely coupled to the second flexure mode of motion, and since this coincides with the longitudinal mode when the width-length

[2] "Electrical Wave Filters Employing Quartz Crystals as Elements," W. P. Mason, *B.S.T.J.*, Vol. 13, July, 1934, pp. 405–452 (see Appendix).

ratio is about 0.25, a coupled-frequency curve for a $+5°$ crystal results as shown in Fig. 17.3. This curve shows the natural frequency for a crystal 1 centimeter long, 0.05 centimeter thick, and having a width-to-length ratio shown by the ordinates. The effect of the shear coupling and flexure coupling are also evident in the temperature coefficient. When the width-length ratio is 0.1 or less, the coefficient is nearly zero. As the ratio increases, the coefficient becomes sharply negative in the region of the flexure coupling, as shown in Fig. 17.4. Above this region the coefficient becomes progressively more negative as the shear-mode frequency approaches the longitu-

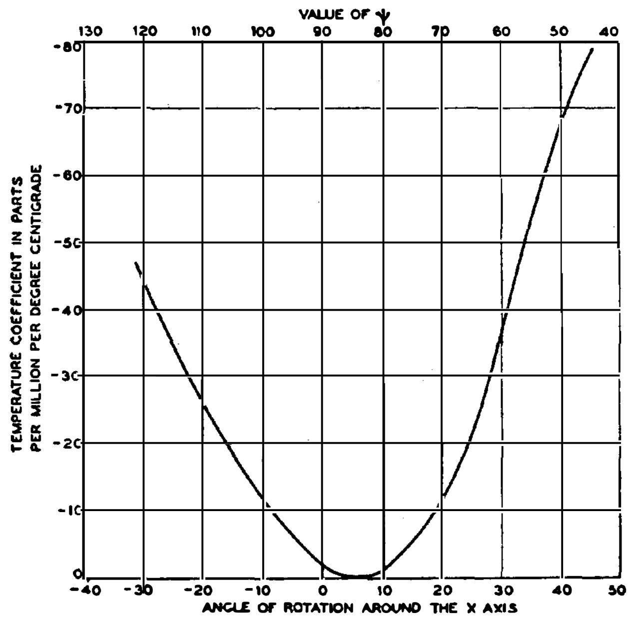

Fig. 17.2—Temperature coefficients of rotated X-cut bars

dinal frequency. This change in temperature coefficient is caused by the high negative temperature coefficient of the face shear mode. The result is that for crystals half as wide as they are long, which is the usual ratio of interest, temperature coefficients of -4 parts per million per °C are as low as can be obtained. Due, however, to the small ratio of capacitances (around 125) that can be obtained with this crystal, it has been used quite extensively in filter work. It is feasible to use this crystal from 50 to 500 kc since the length will vary from 5.6 centimeters to 0.56 centimeter for this range.

When it is desirable to obtain frequencies lower than 50 kc it is usually

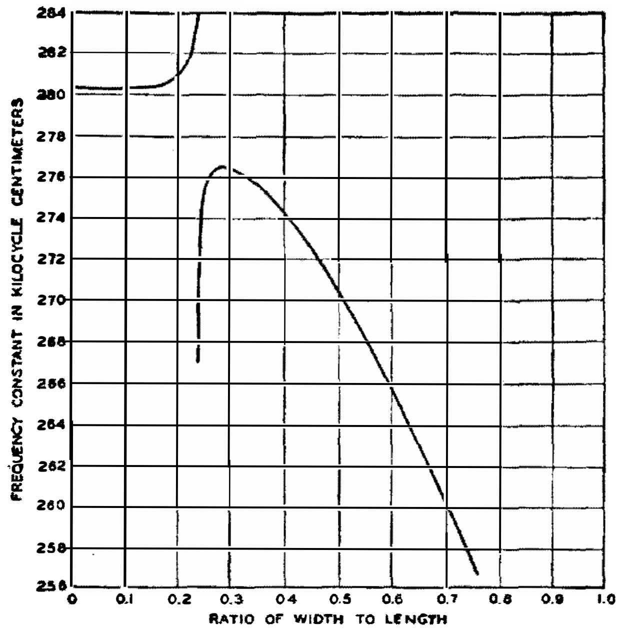

Fig. 17.3—Frequency constant of a +5-degree X-cut crystal as a function of the ratio of width to length

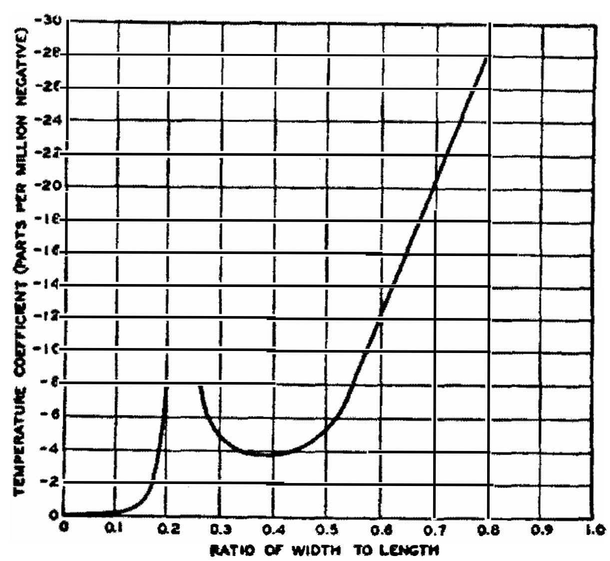

Fig. 17.4—Temperature coefficient of a +5-degree X-cut crystal as a function of the ratio of width to length

not feasible to obtain them by crystals in longitudinal or shear vibrations on account of the large sizes of the crystals required. For lower frequencies it is the flexure mode of motion that can be used, since the frequency obtainable for a flexure crystal is lower for a given size crystal than for any other mode of motion. A flexure crystal with free ends, as shown in Fig. 17.5, is one which expands along one side and contracts along the other. Such a motion can be set up in a longitudinally vibrating crystal, by the use of two sets of platings, the top set charged in different polarity from the bottom set. This causes one side to expand and the other side to contract, thus setting up a flexural motion. When the length of the crystal is large compared to its width, points at 0.224 of the length from each end will be nodal points of the motion and hence will not move appreciably. These points can then be used as supporting points for the crystal. Fig. 17.5 shows the platings cut with small ears at these nodal points. The crystal can be clamped at these points if desired, but the usual method is to solder small wires to the crystals on both sides at the two nodal points and to use the four wires as mechanical supports and electrical connections. Care has to be taken to attach the wires so that they are not antiresonant near the

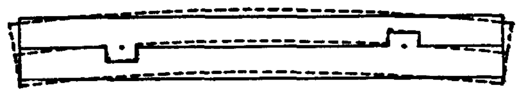

Fig. 17.5—Lowest "free-free" flexure mode of motion

flexure frequency of the crystal for otherwise the characteristics of the wire support would appear in the measured resonance of the crystal.

The first crystal used as a flexure crystal was the $+5°$ X-cut crystal since again it produces the lowest temperature coefficient of any X-cut crystal. This follows from the frequency equation of a long thin crystal

$$f = m^2 l_w / 2\pi\sqrt{12}\sqrt{s'_{22}\rho}\, l^2 \tag{17.1}$$

where s' is the compliance modulus (inverse of Young's modulus) along the length of the crystal, ρ is the density, l_w is the width of the crystal, l is the length of the crystal, and m is a constant depending on the order of the flexure mode. For a crystal free on the ends in its lowest mode of motion, $m = 4.73$. If we differentiate (17.1) with respect to the temperature T and divide through by the frequency, we have

$$T_f = \frac{(df/dT)}{f} = T_{l_w} - [\tfrac{1}{2}[T_{s'_{22}} + T_\rho] + 2T_l] \tag{17.2}$$

where the temperature coefficient of any quantity α is defined as $(d\alpha/dT)/\alpha$. Hence, the temperature coefficient of frequency of a long thin crystal vibrating in flexure is equal to the temperature coefficient of expansion of the width minus twice this coefficient for the length, minus 1/2 the sum of the coefficients of s'_{22} and the density ρ. The temperature coefficient of expansion along the optic axis is 7.8 parts per million per °C, whereas in the plane perpendicular to this axis, the coefficient is 14.3 parts per million. For any direction making an angle θ with the optic axis, the coefficient will be

$$T_l = 7.8 + 6.5 \sin^2 \theta. \tag{17.3}$$

Hence, if A_2 is taken as the angle of the length from the Y axis of the crystal,

$$T_l = 7.8 + 6.5 \cos^2 A_2 \tag{17.4}$$

while the coefficient of the width is

$$T_{l_w} = 7.8 + 6.5 \sin^2 A_2. \tag{17.5}$$

Since the total mass of the crystal remains constant independent of temperature, the temperature coefficient of the density will be the negative of the sum of the temperature coefficients of expansion of the three axes or

$$T_\rho = -36.4. \tag{17.6}$$

The variation of the temperature coefficient of s'_{22} as a function of A_2 can be obtained from the temperature coefficient of frequency for a long thin crystal in longitudinal vibration given by Fig. 17.2. This follows since the frequency of a long thin bar is given by

$$f = 1/2l\sqrt{\rho s'_{22}} \quad \text{and} \quad T_f = -[T_l + \tfrac{1}{2}(T_\rho + T_{s'_{22}})]. \tag{17.7}$$

Inserting the values of T_l and T_ρ, we have for a longitudinal crystal

$$\text{(longitudinal) } T_f = 10.4 - 6.5 \cos^2 A_2 - (1/2)T_{s'_{22}}. \tag{17.8}$$

Since the temperature coefficient of frequency for $A_2 = +5°$ is nearly zero, the value of $T_{s'_{22}}$ for this angle is $+7.9$. At the same angle, the temperature coefficient for a long thin flexure crystal should be

$$\begin{aligned} \text{(flexure) } T_f = {} & 10.4 + 6.5 (\sin^2 A_2 - 2 \cos^2 A_2) \\ & - (1/2)T_{s'_{22}} = -6.4. \end{aligned} \tag{17.9}$$

Since the variation of $\cos^2 A_2$ in this region is small, whereas the variation of $T_{s'_{22}}$ is large, the lowest coefficient for a flexure crystal occurs at the same angle as for a longitudinal crystal.

The frequency equation (17.1) and the temperature-coefficient equation (17.2) for a long thin crystal vibrating in flexure hold only when the crystal is long compared to its width. As the width increases, two other factors affect the frequency equation and temperature coefficient. These are the rotary inertia of a section about its center as an axis, and the shear forces set up by the motion. Both of these factors cause the frequency to increase less than in proportion to the width. These effects are shown by the frequency curve of Fig. 17.6 which plots the frequency of a $+5°$ X-cut crystal 1 centimeter long, 0.05 centimeter thick and with various width-length ratios. Initially, the frequency increases proportionally to the width but for larger width-length ratios, the increase is less, and the frequency approaches an asymptotic value. The effect of the shear stresses is shown by the temperature-coefficient curve of Fig. 17.7, which plots the coefficient as a function of the length-width ratio. For a long thin crystal, the coefficient is about 6 parts in a million negative in agreement with (17.9). For larger ratios the

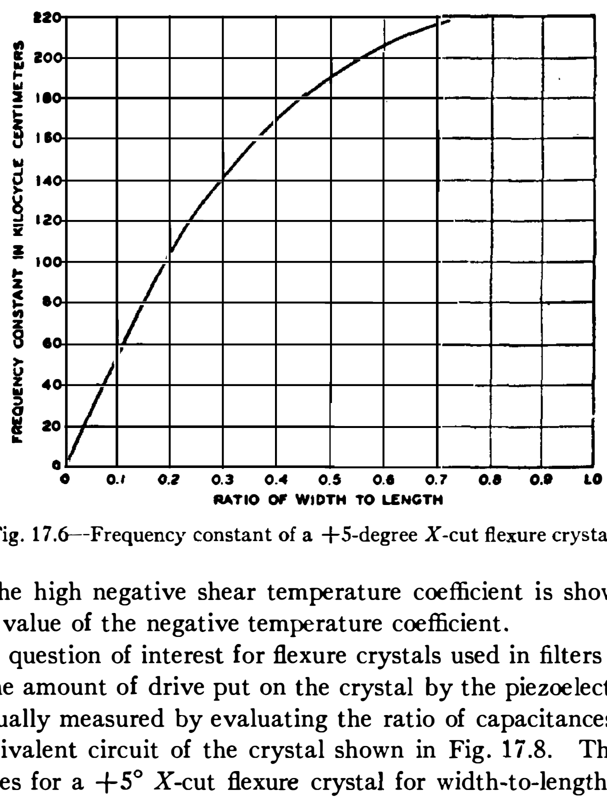

Fig. 17.6—Frequency constant of a +5-degree X-cut flexure crystal

effect of the high negative shear temperature coefficient is shown by the increasing value of the negative temperature coefficient.

Another question of interest for flexure crystals used in filters and oscillators is the amount of drive put on the crystal by the piezoelectric effect. This is usually measured by evaluating the ratio of capacitances C_0 to C_1 in the equivalent circuit of the crystal shown in Fig. 17.8. The ratio of capacitances for a $+5°$ X-cut flexure crystal for width-to-length ratios up to 0.4 is around 180, whereas the ratio for a longitudinal crystal is 125. This agrees well with a theory worked out for a flexure crystal[3] which shows that the ratio of capacitances of a crystal driven in flexure should be $128/9\pi^2$

[3] "Electromechanical Transducers and Wave Filters," W. P. Mason, D. Van Nostrand Company, New York, N. Y., 1942, p. 215.

times that for the same crystal driven in a longitudinal mode. The Q obtainable with a wire-supported flexure crystal in an evacuated container is quite high, i.e., greater than 30,000. The effect of the air loading on a flexure crystal is larger than for a longitudinal crystal both as to frequency reduction and Q reduction.

17.3 *MT* Low-Coefficient Longitudinally Vibrating Crystal

The *MT* low-coefficient longitudinally vibrating crystal grew out of the data of Fig. 17.4, which shows that an increase of width causes a closer coupling to the shear mode and hence a high negative temperature coefficient as the width-length ratio is increased. If a crystal can be obtained with the

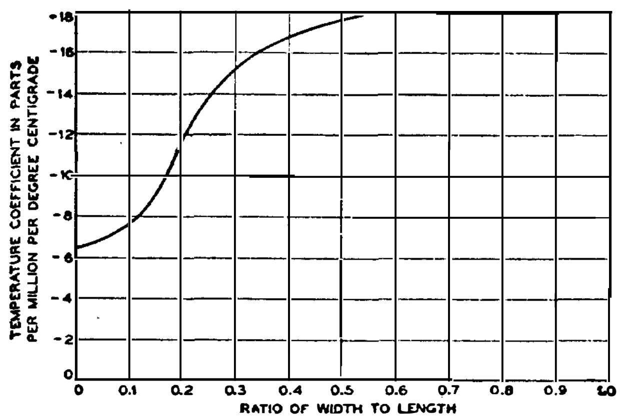

Fig. 17.7—Temperature coefficient of a +5-degree X-cut flexure crystal

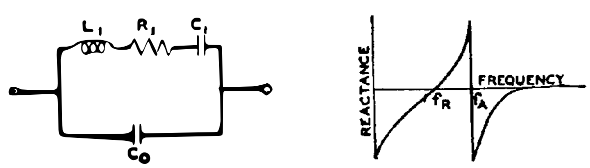

Fig. 17.8—Equivalent circuit of a crystal vibrating in flexure

same longitudinal constants but with a face shear having a lower or zero temperature coefficient, the large increase in temperature coefficient should not take place as the width-length ratio is increased. Such a crystal can be obtained by maintaining the same length direction in the crystal (which gives the same compliance modulus s'_{22} along the length) and rotating the normal to the major surfaces away from the X axis. This has the effect of changing the temperature coefficient of the face shear mode from highly negative through zero to highly positive.

To show this, use can be made of an analysis of the temperature coefficient of the face shear mode given in a previous paper.[4] If we translate (21) of that paper into an expression involving the I.R.E. orientation angles, we have

$$T_f = 10.4 - 3.25 \sin^2\theta + \left[\frac{\begin{array}{l} -5877.5 \sin^4\theta \sin^2 2\psi + 15{,}790 \cos^2\theta \\ \quad + 2655\,[\sin 2\theta \sin 3\phi (2\cos^2 2\psi - \sin^2 2\psi(1 + \cos^2\theta)) \\ \quad + \sin 4\psi \cos 3\phi \sin\theta (1 + 3\cos^2\theta)] \\ \qquad - 19{,}525\left(\sin^2\theta\cos^2 2\psi + \dfrac{\sin^2 2\psi \sin^2 2\theta}{4}\right) \end{array}}{\begin{array}{l} 195 \sin^4\theta \sin^2 2\psi + 292.8 \cos^2\theta \\ \quad - 43.1\,[\sin 2\theta \sin 3\phi (2\cos^2 2\psi - \sin^2 2\psi(1 + \cos^2\theta)) \\ \quad + \sin 4\psi \cos 3\phi \sin\theta (1 + 3\cos^2\theta)] \\ \qquad + 200.5\left(\sin^2\theta\cos^2 2\psi + \dfrac{\sin^2 2\psi \sin^2 2\theta}{4}\right) \end{array}}\right]. \quad (17.10)$$

For purposes of illustration, let us consider an X-cut crystal with its length along the Y axis ($\phi = 0$, $\theta = 90°$, $\psi = 90°$). For this condition (17.10), shows that the face shear mode has a negative temperature coefficient of -90.2.

If now the length is kept along the Y axis but the normal to the principal surface is rotated from the X axis ($\phi = 0$; $\theta =$ variable; $\Psi = 90°$), the equation for the temperature coefficient of the face shear mode becomes

$$T_f = 10.4 - 3.25 \sin^2\theta + \left[\frac{15{,}790 \cos^2\theta - 19{,}525 \sin^2\theta}{292.8 \cos^2\theta + 200.5 \sin^2\theta}\right]. \quad (17.11)$$

As the normal is rotated from the X axis the coefficient of the shear mode becomes less negative and passes through zero when the angle from X is 40° ($\theta = 50°$ or $\theta = 130°$). The expectations are then that with a crystal cut at one of these orientations the large increase in the negative temperature coefficient should not occur with an increase in the width-length ratio.

Such a crystal was obtained and its properties measured as a function of the width-length ratio. The temperature coefficient starts out at -2 parts per million per °C, when the width-length ratio is 0.1 or less in agreement with the result found for the X-cut crystal. As the width increases, the large increase in coefficient does not occur as with the X-cut. Instead the coefficient is uniformly low over the whole region. The frequency constant and the ratio of capacitances are also shown in Fig. 17.9. As might be expected, the ratio of capacitances for this crystal is higher than for an X-cut crystal, since the piezoelectric constant decreases as the normal varies

[4] "Low Temperature Coefficient Quartz Crystals," W. P. Mason, *B.S.T.J.*, Vol. 19, Jan., 1940, pp. 74–93.

from the X axis. For a general orientation it can be shown that the d'_{31} piezoelectric constant is given by the equation

$$d'_{31} = d_{11} \sin\theta[\cos 3\phi(\cos^2\theta\cos^2\phi - \sin^2\psi) - \sin 2\psi \sin 3\phi \cos\theta] - (d_{14}/2)\sin^2\theta \sin 2\psi. \tag{17.12}$$

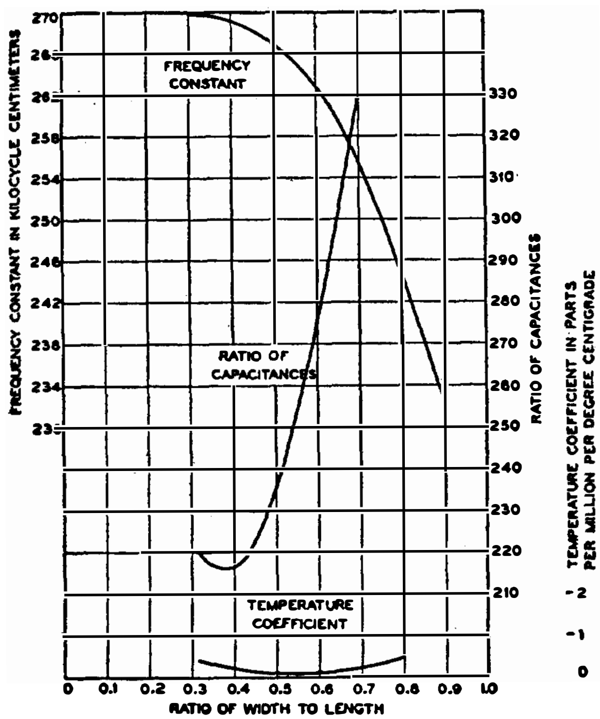

Fig. 17.9—Frequency constant, ratio of capacitances, and temperature coefficient of a crystal with its length along the Y axis and the normal to the principle surface at an angle of 45 degrees from the X axis.

For this orientation ($\phi = 0$, $\theta = 50$ or $130°$, $\Psi = 90°$) it has a value of 76.6% of the constant for an X-cut crystal resulting in a larger ratio of capacitances for the crystal.

The initial value of -2 parts per million per °C found for this crystal can be lowered, if the length is taken in the same direction as the $+5°$ X-cut crystal. By rotating the normal to the principal plane about this axis, the face shear mode can be made to have a zero coefficient at a rotation of $\pm 40°$ which is slightly less than for the first cut described. The characteristics of this crystal are shown by Fig. 17.10 and are somewhat more favorable than the $\phi = 0; \theta = 50$ or $130°; \Psi = 90°$ crystal. Fig. 17.11 shows a further measurement when the length is at an angle of $A_2 = +8.5°$ from the Y axis and the normal to the surface rotated by $\pm 34°$. A typical temperature-frequency curve of this crystal, with ratio of width to length = 0.42, used to control an oscillator is shown by Fig. 17.12. The curvature as with most quartz crystals is negative and about the same order as the CT crystal. This series of crystals has been designated the MT cuts. They comprise those crystals that have angles A_2 from 0 to $+8.5°$, and angles of rotation

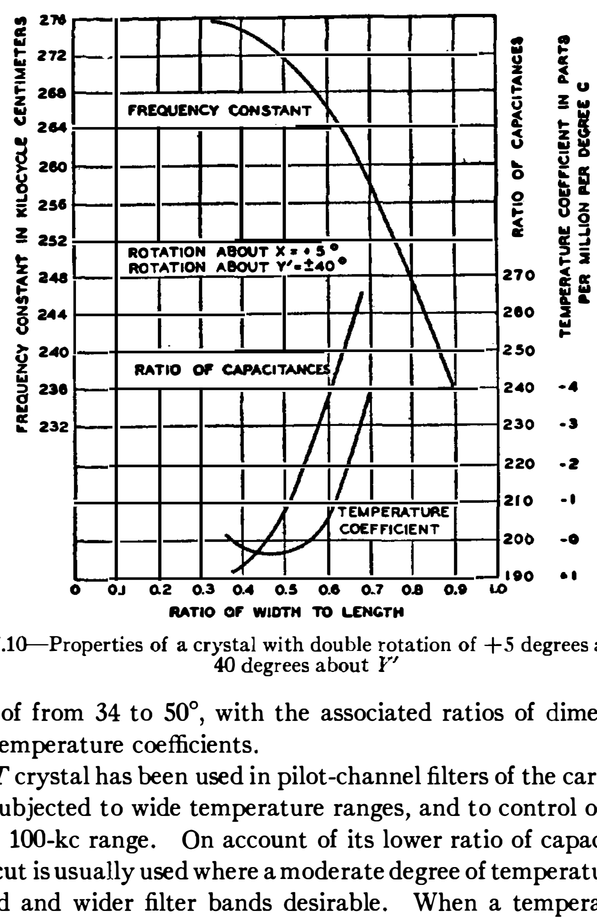

Fig. 17.10—Properties of a crystal with double rotation of +5 degrees about X, 40 degrees about Y'

about Y' of from 34 to 50°, with the associated ratios of dimensions that give low temperature coefficients.

The MT crystal has been used in pilot-channel filters of the carrier system, that are subjected to wide temperature ranges, and to control oscillators in the 50- to 100-kc range. On account of its lower ratio of capacitances the $+5.0°$ X-cut is usually used where a moderate degree of temperature stability is required and wider filter bands desirable. When a temperature coefficient of 25 parts in a million can be tolerated and a freedom from secondary modes of motion desirable, as in the band-selection filters of the carrier systems, the $-18.5°$ X-cut crystal is still preferable.

17.4 The *NT* Flexure Low-Coefficient Crystal

The method of obtaining a low-coefficient flexure crystal from a $+5°$ X-cut crystal is the same as that for a longitudinal crystal, namely, rotating the normal to the principal surface away from the X axis. Furthermore, this procedure will not only neutralize the negative coefficient put in by the shear stresses but will also lower the coefficient for a long thin crystal where the effect of the shear stresses is negligible. This follows from the

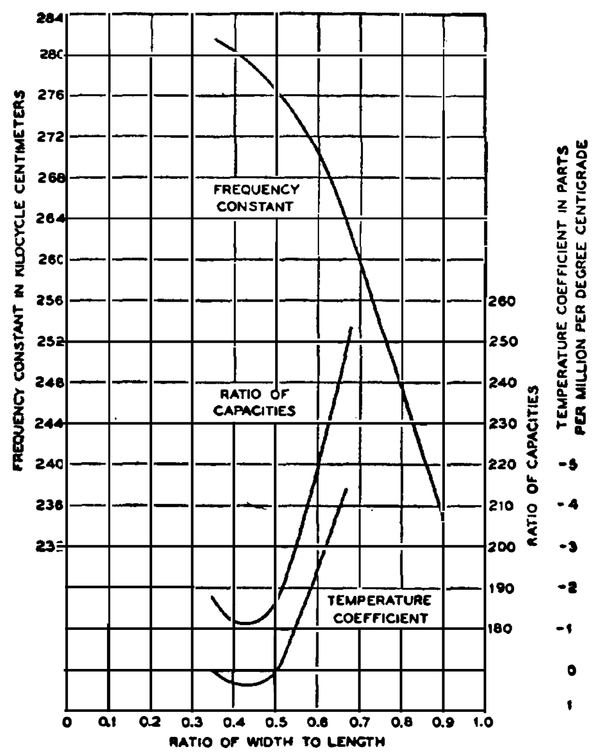

Fig. 17.11—Properties of a crystal with double rotation of $+8.5$ degrees about X, 34 degrees about Y'

fact that the width direction changes from being nearly along Z (where its expansion coefficient is small) to being nearly along X (where its expansion coefficient is larger). For a 90° rotation the flexure vibration has the same coefficient as the longitudinal vibration, that is, nearly zero. Since, however, the piezoelectric modulus disappears at this angle, it cannot be used. A useful compromise is effected by using a rotation angle of 50 to 70°.

Fig. 17.13 shows the temperature coefficient at 30°C as a function of width to length for several doubly oriented crystals. If a width-to-length ratio of 0.2 to 0.5 is to be used, low coefficients are obtained by using angles of rotation about X of from 0 to $+8.5°$, and a 50° rotation about the resulting Y' axis. Fig. 17.14 shows the corresponding frequency constants and ratios of capacitances for these crystals as a function of frequency.

For lower ratios of axes and consequently for lower frequencies, a higher rotation about the Y' axis should be employed. Fig. 17.15 shows the relation between a rotation about the X axis and rotation about the Y' axis to give

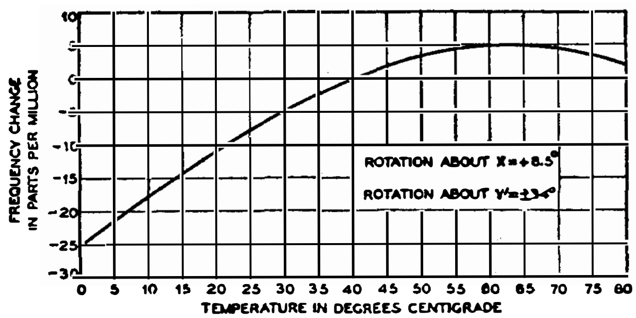

Fig. 17.12—Change in frequency of an MT crystal over a wide temperature range

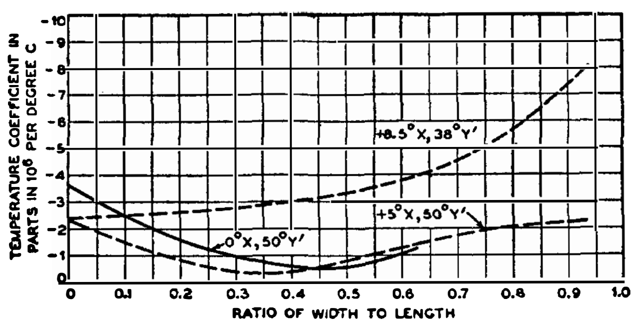

Fig. 17.13—Temperature coefficients of low-frequency *NT* flexure crystals

a zero coefficient at 25°C for a crystal, whose width is 5% of its length. Crystals of this type have been used with the Western Electric frequency-modulation broadcast transmitter.[1] Operating in the region of 5 kc they maintain the frequency of the transmitter constant to ±0.0025% without temperature control.

The wider crystals with ratios from 0.2 to 0.5 have been used in the pilot-channel filters of the cable-carrier system to pick off pilot frequencies from 10 to 50 kc.

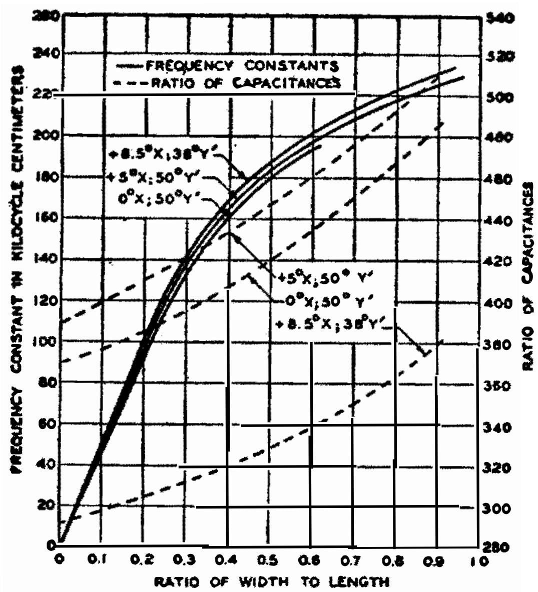

Fig. 17.14—Frequency constants and ratios of capacitances of low-frequency NT flexure crystals

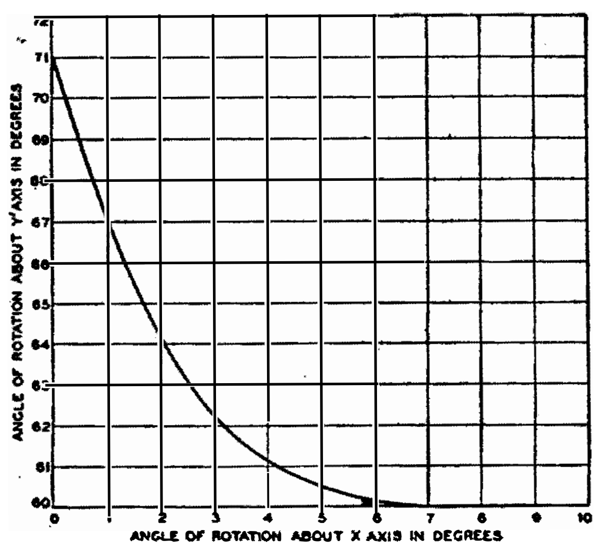

Fig. 17.15—Locus of angular orientations about X and Y' to produce a zero temperature coefficient for long thin NT flexure crystals

17.5 Oscillator Circuit for Driving Low-Frequency *NT* Crystals

Because of the small capacitance and high impedance of these low-frequency crystals, they do not work well in conventional oscillator circuits. Consequently, some work has been done in developing an oscillator circuit for which they will function satisfactorily. The circuit employed is shown in Fig. 17.16. The feedback from plate to grid occurs through the four-electrode crystal. The plate circuit of the tube is connected to the terminals 1 and 2 in Fig. 17.17 while the grid is connected to terminal 4. Terminals 2 and 3 are connected together and connected to ground through

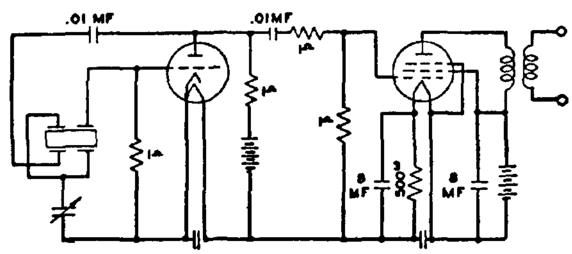

Fig. 17.16—Oscillator circuit for driving a low-frequency flexure crystal

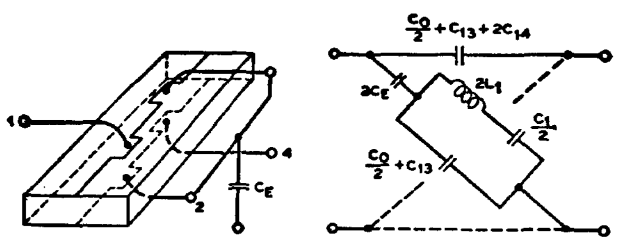

Fig. 17.17—Crystal connections and equivalent circuit for a flexure crystal used to obtain a phase reversal

a variable condenser, which allows the frequency to be varied by 50 to 60 parts in a million. In order that sufficient output may be obtained an amplifier has been added. To reduce the effects of change in input impedance of the amplifier a loss network is added between tubes. Thus, a change in the load impedance or supply voltage will have little effect upon the oscillator.

The connection of terminal 1 to the plate, terminals 2 and 3 to ground, and terminal 4 to the grid reverses the input current by 180° at the resonant frequency of the crystal. Since the tube itself introduces a 180° phase shift, this allows the oscillator to work at the resonant frequency of the crystal. As pointed out in a previous paper,[5] this is the condition for maximum stability at maximum oscillator output. The effect of the capacitance C_B between ground and the terminals 2, 3 can be analyzed as was done for the case of a longitudinal crystal with two sets of plates recently.[6] Employing the same analysis, it can be shown that the three-terminal crystal with capacitance C_B to ground is equivalent to the lattice network of Fig. 17.17, where $C_0/2$ is the static capacitance of one set of the crystal platings, L_1, C_1, and R_1 the equivalent motional inductance, capacitance, and resistance of a completely plated crystal, C_{14} is the stray capacitance from terminal 1 to terminal 4, and $C_{13} = C_{24}$ is the stray capacitance from terminal 1 to terminal 3, which from symmetry is equal to that from terminal 2 to terminal 4. When C_B is large the impedance of the lattice branch at the crystal resonant frequency will be the resonance resistance of the crystal which is small in impedance compared to the reactance of the shunt capacitance of the series arm. Therefore, the circuit will reverse the phase of the input and the oscillator will work at the crystal resonant frequency. As C_B becomes smaller, the resonance of the lattice arm will increase in frequency and also in effective resistance. By this means the oscillator frequency can be varied by 50 to 60 parts in a million, thus allowing a wider tolerance for the resonant frequency of the crystal.

Fig. 17.18 shows a photograph of a crystal mounted in a special vacuum-tube case. Electrical connection as well as mechanical shockproof mounting is obtained by soldering 0.005-inch phosphor-bronze wires to the plated areas on the crystal. To allow for severe shocks due to accidental drops and shipping, mica supports have been provided. This type of cage support has been used for the coaxial filter crystals and was originally developed by A. W. Zeigler.

Some performance data for this oscillator are shown in Fig. 17.19. Curve A shows the variation of frequency with supply voltage to the oscillator. Large variations in the order of 50% in load or supply voltage to the amplifier produce a frequency change of less than 1 part in a million. The frequency-temperature characteristic is shown in curve B and is similar to the MT type. It is necessary to maintain a high Q and be free of other modes of motion in the crystal as well as the support wires to produce the characteristic shown in curve B. A typical aging characteristic is shown by curve C.

[5] "A New Direct Crystal-controlled Oscillator for Ultra-short-wave Frequencies," W. P. Mason and I. E. Fair, *Proc. I.R.E.*, Vol. 30, Oct., 1942, pp. 464–472.

[6] See Chapter VIII, Fig. 8.8, of book in footnote 3. For a flexure crystal, since the two sets of plates, if of the same polarity, produce opposite effects in driving the flexure mode, the numbering of the output terminals has to be interchanged to get the same equivalent circuit.

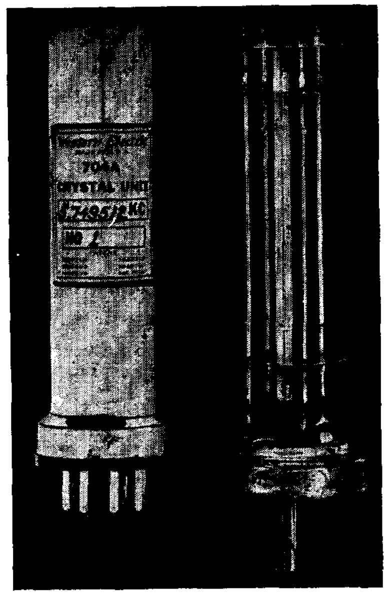

Fig. 17.18—Photograph of *NT* flexure crystal and holder

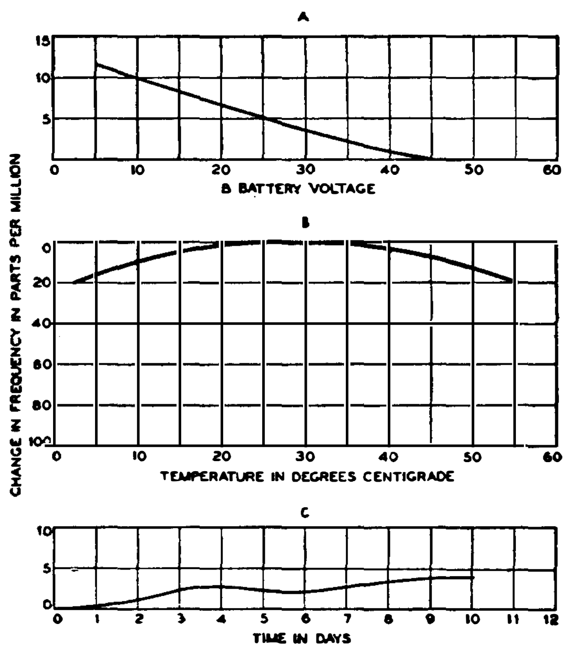

Fig. 17.19—Perf●rmance data for *NT* crystal-controlled oscillator

A crystal of this type was first used in the Mutual Broadcasting Company's experimental frequency-modulation transmitter W2XOR operating at 43.5 mc. A bimonthly check of the transmitter over a period of four months showed a maximum frequency change of less than $\pm 0.0006\%$.

Summary

This Chapter discusses low-frequency, low-temperature-coefficient crystals which are suitable for use in filters and oscillators in the frequency range from 4 to 100 kc. Two new cuts, the *MT* and *NT*, are described. These are related to the $+5°$ *X*-cut crystal, which is the quartz crystal having the lowest temperature coefficient for any orientation of a bar cut from the natural crystal. When the width of the $+5°$ *X*-cut crystal approaches in value the length, the motion has a shear component, and this introduces a negative temperature coefficient which causes the temperature coefficient of the crystal to become increasingly negative as the ratio of width to length increases.

The *MT* crystal has its length along nearly the same axis as the $+5°$ *X*-cut crystal, but its major surface is rotated by 35 to 50° around the length axis. This results in giving the shear component a zero or positive temperature coefficient and results in a crystal with a uniformly low temperature coefficient independent of the width-length ratio. A slightly higher rotation about the length axis results in a crystal which has a low temperature coefficient when vibrating in flexure and this crystal has been called the *NT* crystal. The *NT* crystal can be used in a frequency range from 4 to 50 kc, while the *MT* is useful from 50 kc to 500 kc.

A special oscillator circuit is described which can drive a high-impedance *NT* flexure crystal. This circuit together with the *NT* crystal has been used to control the mean frequency of the Western Electric frequency-modulated radio transmitter.