

# TECHNICAL INSTRUCTION

T.2

*Quartz Oscillators*

*BBC Crystal-drive Equipments*

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AMENDMENT RECORD

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## QUARTZ OSCILLATORS BBC CRYSTAL-DRIVE EQUIPMENTS

### SECTION A QUARTZ OSCILLATORS

#### Quartz Crystals

This section deals with the properties and preparation of the quartz plates used as frequency control elements in certain types of BBC transmitter drive equipment.

Quartz is a common natural form of silica ( $\text{SiO}_2$ ), but crystals of a size and type suitable for the preparation of frequency-control elements are found in quantity only in a few countries, principally Brazil, Madagascar and Japan.

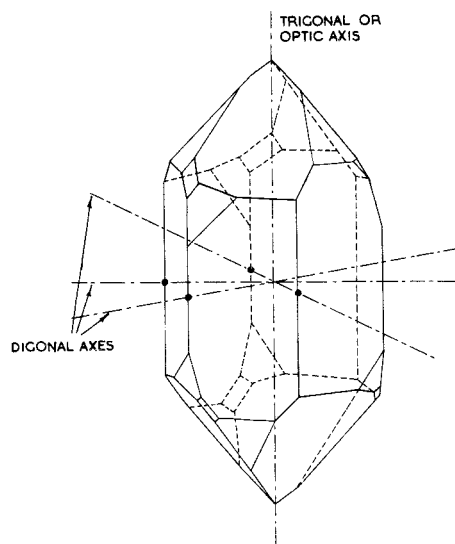


Fig. A.1. Quartz Crystal of Perfect Form, Showing Crystallographic Axes of Symmetry

Fig. A.1 shows one of the two possible forms of a perfect quartz crystal, the crystal illustrated being known as a *left-handed* crystal. The alternative form, which would be represented by the mirror image of Fig. A.1 is referred to as a *right-handed* crystal. The perfect crystal has the form of a regular hexagonal prism terminated at both ends in a pyramid having three large and three small faces. In addition small facets appear on

alternate prism edges. The crystal is asymmetrical in that each side of the prism is terminated at one end in a small pyramid face and at the other end in a large pyramid face.

Fig. A.2 indicates the lettering of the crystal faces and facets in accordance with the National Physical Laboratory notation (with the exception that, to avoid possible confusion, the *m*-under-R and *m*-under-z faces are distinguished by using *m* for the former and *m'* for the latter). The perfect crystal possesses six R, six z, three *m* and three *m'* faces, and also six *s* and six *x* facets.

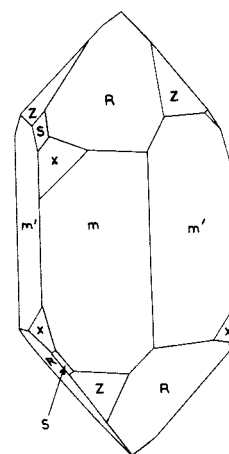


Fig. A.2. Letter Notation for Main Faces and for Facets of Crystal

The quartz crystal has one trigonal and three digonal axes of symmetry (Fig. A.1). The line joining the vertices of the pyramids is an axis of trigonal symmetry, that is, the same configuration is repeated at every  $120^\circ$  of rotation of the crystal about this axis. It is also known as the principal or optic axis, the latter name being given because a beam of plane-polarized monochromatic light passed through the crystal in a direction parallel to this axis undergoes rotation

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of its plane of polarisation. The three axes of digonal symmetry are in a plane at right angles to the principal or optic axis and are parallel to the  $m$  and  $m'$  faces of the prism. They are so named because the same configuration is repeated at every  $180^\circ$  of rotation of the crystal about these axes.

### Piezo-electric Properties

If a quartz crystal is subjected to mechanical stresses in the direction of any one of the digonal axes equal electric charges are set up on the edges of the prism, alternate edges carrying charges of opposite sign. If the mechanical stresses are reversed the signs of the charges are reversed also.

Similarly, a mechanical stress applied in a direction perpendicular both to a digonal axis and to the optic axis will produce charges on the prism edges. A compressional stress applied in this direction will produce charges of opposite signs to those produced by a compressional stress applied along the digonal axis.

This effect which is known as the 'direct' piezo-electric effect is reversible. That is to say, a potential difference applied in the direction of a digonal axis, or in a direction perpendicular both to a digonal axis and to the optic axis, will produce mechanical stresses in the directions of the digonal axes and perpendicular to the latter. This effect is known as the 'converse' piezo-electric effect.

Several crystalline materials are known to possess piezo-electric properties, e.g., quartz, tourmaline, and rochelle salt (potassium sodium tartrate), but this Instruction deals only with quartz.

### X, Y and Z Axes

The piezo-electric properties of a quartz crystal are usually expressed with reference to three axis-directions, X, Y and Z. It is important to note that references to X, Y and Z axes are references to *directions* and not to specific single axes.

A Z-axis direction is parallel to the optic axis, an X-axis direction is parallel to an  $m$  or  $m'$  face and also perpendicular to the Z-axis direction, while a Y-axis direction is perpendicular both to the Z- and to the X-axis directions. Fig. A.3 shows the cross-section of the prism of a quartz crystal of ideal form and the diagram indicates the X- and Y-axis directions. The Z-axis direction is perpendicular to the cross-section plan shown in the figure.

Fig. A.4 shows the cross-section of the prism of a crystal of irregular form, as commonly found. X- and Y-axis directions are shown and it will be observed that the X axes are parallel to  $m$  or

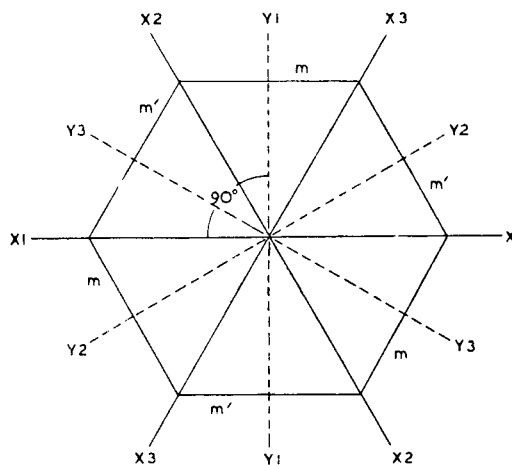


Fig. A.3. Cross-section of Ideal Crystal showing Directions of X and Y Axes

$m'$  faces, while the Y axes are perpendicular to the X axes. The Z axis is perpendicular to the cross-section. The irregularity of the crystal form does not alter the fundamental orientation

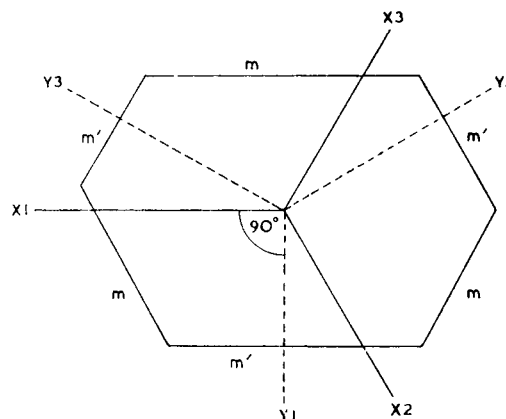


Fig. A.4. Cross-section of Imperfectly-formed Crystal showing Directions of X and Y Axes

of the axes as described above for the ideal crystal form.

Quartz crystals in the natural state generally taper along the prism length and the prism is not of regular hexagonal cross-section, although such deformation does not necessarily make a specimen

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unsuitable for piezo-electric applications. Crystals which are too small to permit the cutting from them of plates having the required dimensions and orientations, or those in which there is extensive 'twinning' are, however, useless. The term 'twinning' describes a complex molecular structure resulting in either a combination of left-hand and right-hand crystal forms, or a combination in which part of the crystal is rotated 180° about the optic axis with reference to the remainder of the crystal. There may even be both these kinds of deformation in the one crystal.

No matter how irregular a crystal may be in its geometrical form the included angle between adjacent  $m$  and  $m'$  faces is always 120°. Furthermore, the included angle between an R face and the optic axis is always 41° 47'.

Quartz is selected for piezo-electric applications after optical, X-ray and electrical tests to determine the extent of homogeneity of its molecular structure. Suitable specimens are then tested to identify the faces and to determine the axis directions. The cutting of individual plates is carried out by means of high speed circular saws, consisting of thin copper or bakelite discs whose edges are charged with diamond dust.

### Quartz-crystal Plates for Oscillators

If a plate cut at a suitable orientation from a natural quartz crystal is mounted between two electrodes and a potential difference is applied between the latter, mechanical stresses will be produced in the plate which will then undergo deformation. If the potential difference is removed the plate will not resume its former shape immediately but will execute a series of mechanical vibrations of decreasing amplitude, the frequency and nature of which will be determined by the density and elasticity of the quartz and the dimensions of the plate.

If an alternating potential difference is applied to the electrodes the crystal plate will respond in an analogous manner to an oscillatory circuit to which an alternating e.m.f. is applied. When the applied frequency is near the natural frequency of the crystal a condition approaching mechanical resonance occurs and the crystal vibrations build up to a comparatively large amplitude.

The crystal vibrations will set up alternating potential differences between the electrodes and the resulting alternating voltage may be applied to an amplifier and a feed-back circuit to maintain continuous oscillations.

The general formula for the frequency of vibration of a crystal plate, in any direction, is as follows:—

$$f = \frac{1}{2t} \sqrt{\frac{c}{d}}$$

where  $f$  = frequency in c/s

$t$  = dimension of plate, in the direction of vibration, in cms

$d$  = density of quartz in gms/cm<sup>3</sup>

$c$  = elastic constant, in the direction of vibration, in dynes/cm<sup>2</sup>

For any plate of given dimensions and orientation of cut the frequency expression can be given in the following form:—

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

The term  $k$  is known as the frequency constant and is normally expressed in kc/s per mm.

A temperature term does not appear in the general expression for frequency given above, but the various terms contained in the expression are not independent of temperature. To what extent the resonant frequency of a crystal plate will change with a given change of its temperature will depend upon the individual variations, with temperature, of the terms given in the expression.

(The temperature-frequency coefficient of a crystal plate is the change of frequency per unit change of temperature and is usually expressed as so many parts in 10<sup>6</sup> per degree Centigrade rise of temperature.)

The temperature coefficient varies widely according to the angle of orientation, relative to the X, Y and Z axes, at which the plate was cut from the natural crystal and there are certain specific orientations at which there is a balance between the temperature coefficients of the elastic constant, and of the other terms in the frequency formula, resulting in an almost zero temperature-frequency coefficient for the plate.

A crystal plate sometimes has two modes of vibration, one of which produces the desired frequency of oscillation. Any elastic coupling between two modes of vibration will tend to produce double-frequency effects which are dependent, as regards magnitude, upon the extent of the coupling and upon the frequency relationship between the coupled modes. Undesirable results can occur in cases where one of the principal modes of vibration occurs at a frequency equal, or nearly equal, to a harmonic of one of the other modes of

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vibration. In cases where two modes of vibration have temperature-frequency coefficients of opposite sign there may, under certain conditions, be sudden and random changes of frequency, this effect being particularly pronounced in a Y-cut plate.

Certain specific orientations of crystal cut give zero value for the constant of elastic coupling. These particular crystal cuts, however, are not necessarily those which provide zero temperature-frequency coefficients.

#### Types of Cut

##### 1. X-Cut Plates

An X-cut plate is shown in Fig. A.5. It is cut from the natural crystal in such a manner that the major surfaces of the plate are in YZ planes and are, consequently, perpendicular to the X-axis direction.

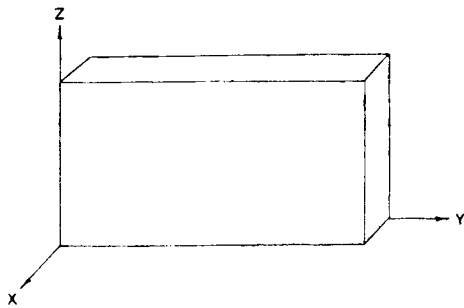


Fig. A.5. X-Cut Plate

If an X-cut plate is placed in an alternating electric field, having a direction parallel to the X axis, it executes extensional vibrations in two modes. One is at a frequency determined by the thickness of the plate, measured in the X direction, while the other is at a frequency determined by the width of the plate, measured in the Y direction. In either case the frequency is given by the expression :

$$f(\text{kc/s}) = \frac{2750}{t} \text{ (approx.)}$$

where  $t$  is the frequency-controlling dimension in millimetres.

The frequency constant varies slightly for different dimensional ratios of plates.

The temperature-frequency coefficient of an X-cut plate is negative and is found in practice to vary between  $-20$  and  $-50$  parts in  $10^6$

per  $1^\circ\text{C}$ . rise in temperature. This is a relatively high value of temperature-frequency coefficient and represents one of the disadvantages of the X-cut plate for oscillator applications.

The thickness mode of vibration is normally the mode used for the generation of the required frequency, and the extensional character of the vibration prohibits the rigid clamping of the plate. Another disadvantage of the use of the thickness mode of vibration in an X-cut plate is that pressure waves are set up in the air columns between the plate and the electrodes of the crystal holder. These air waves have a damping effect on the crystal plate vibrations and, at frequencies at which fundamental (or harmonic) resonance conditions occur between the crystal plate and the air column vibrations, the damping effects can be serious.

##### 2. Y-cut Plates

A Y-cut plate is shown in Fig. A.6. It is cut from the natural crystal in such a manner that the major surfaces of the plate are in XZ planes and are, consequently, perpendicular to the Y-axis direction.

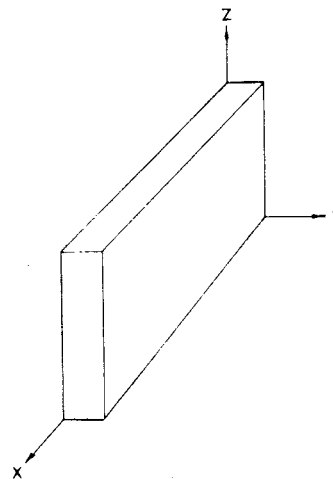


Fig. A.6. Y-Cut Plate

A Y-cut plate can be made to vibrate in an extensional mode as shown in Fig. A.7 and the same frequency constant applies as for an X-cut plate. If, however, an alternating electric field having a direction parallel to the Y-axis is applied, a very active thickness shear vibration occurs, as shown in Fig. A.8.

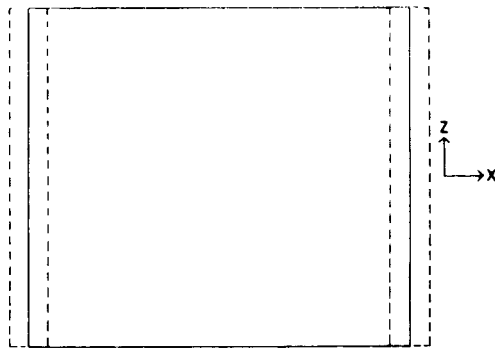
The vibrations in this mode are, therefore



governed by the shear modulus of the crystal in this plane and the frequency is given by the expression :—

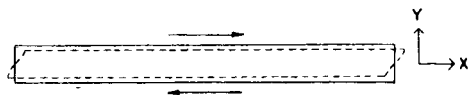
$$f \text{ (kc/s)} = \frac{2070}{t} \text{ (approx.)}$$

where  $t$  is the frequency-controlling dimension in millimetres.



**Fig. A.7. Longitudinal Extensional Mode of Vibration**

The temperature coefficient of the shear modulus is positive, and a Y-cut plate has a temperature-frequency coefficient of about + 70 parts in  $10^6$  per  $1^\circ \text{C.}$  rise in temperature. This statement, however, is only true of very thin plates, that is to say, of plates with a large width to thickness dimensional ratio. When this dimensional ratio is small the temperature-frequency coefficient can no longer be predicted with certainty. It is found



**Fig. A.8. Thickness Shear Mode of Vibration**

that the temperature-frequency coefficient may have any value, including zero, between + 100 and - 20 parts in  $10^6$  per  $1^\circ \text{C.}$  rise in temperature, whilst sometimes a small change of operating temperature or even of circuit values may result in random changes of frequency, termed 'stepping.'

The unreliable performance of Y-cut plates greatly limits their application although in certain other respects they possess desirable properties.

For example, Y-cut plates are more active than X-cut plates and, because they execute shear vibrations, the plates may be clamped in their holders on the nodal plane.

### 3. Cube Crystals

Since X-cut and Y-cut plates have temperature frequency coefficients of opposite sign it follows that if these temperature-frequency coefficients were of equal magnitude a crystal cut in the form of a cube with sides parallel to the X, Y and Z axes would have zero temperature-frequency coefficient (at the appropriate operating temperature). The temperature-frequency coefficients of X-cut and Y-cut plates are not equal and a perfect cube would not, therefore, have zero temperature-frequency coefficient. Nevertheless, it is possible so to proportion the dimensions of the cube that a very low temperature-frequency coefficient is obtained, the result being a crystal block in which the X dimension is approximately 1.18 that of the Y dimension and is equal to the Z dimension. These cube crystals can, however, only be used between frequency limits of approximately 75 kc/s and 750 kc/s and thus it is necessary to use frequency multiplication to produce higher frequencies.

### 4. Inclined Angle Cuts

Fig. A.9 shows a section of a crystal cut in a plane at right angles to the Z axis. From this section two plates are shown cut at different orientations. One plate is a Y-cut plate, obtained when the main cutting planes contain the X and Z axes. The other plate is obtained when the main cutting planes are rotated about the X axis by  $35^\circ 15'$  from the Z axis towards an  $m$  face. This plate is known as an AT-cut plate, in accordance with the notation described below. There are a number of specific orientations of cut, of which the AT-cut is one example, all being simple inclined cuts about the X axis, some of which provide plates having substantially zero temperature-frequency coefficients at particular temperatures while others provide plates possessing negligible coupling between alternative modes of vibration.

A system of notation commonly used in connection with these cuts involves combinations of two letters. Plates cut at angles  $n$ , between  $0^\circ$  and  $+ 90^\circ$  are known as A-cuts (high frequency), and C cuts (low frequency, i.e., 200 kc/s and below). Plates cut at values of  $n$  between  $0^\circ$  and  $- 90^\circ$

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(i.e., away from an  $m$  face) are known as B cuts (high frequency), and D cuts (low frequency). Plates cut at the specific angles giving zero temperature-frequency coefficients are designated by adding the letter T, hence the term AT cut. Plates cut at the specific angles giving zero inter-mode coupling are designated by adding the letter C.

opposite sides of the X axis (angle  $0^\circ$ ). In this figure,  $n$  represents the angle of rotation about the X axis.

The angles for the AT- and AC-cuts are more nearly equal than those for the BT- and BC-cuts. In practice, therefore, the A-cut is favoured, particularly as it is slightly more active than the B-cut. The angle corresponding to minimum

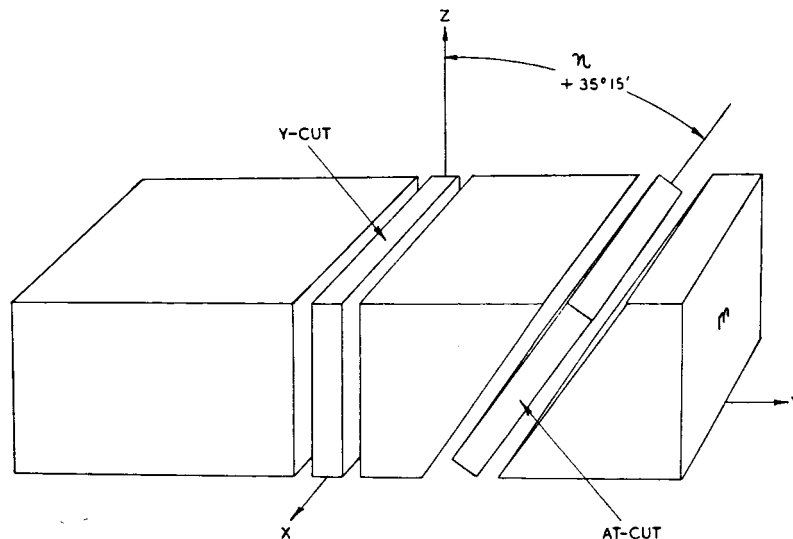


Fig. A.9. AT-Cut shown in Relation to Y-cut

For the sake of clarity only one of the inclined cuts (the AT cut) is shown in Fig. A.9. The following table, however, details simple inclined cuts about the X axis:—

Notation of cut	Value of Angle 'n' (ref. Fig. A.9)
AC	+ 31°
AT	+ 35° 15'
CT	+ 38°
ET	+ 66°
BT	- 49°
DT	- 52° 30'
FT	- 57°
BC	- 59°

The curves of Fig. A.10 show the variation of temperature-frequency coefficient with values of  $n$  from  $-90^\circ$  to  $+90^\circ$ . The full-line curve applies to A- and B-cut plates and the dotted curve to C- and D-cut plates. It will be seen that in both cases the two specific orientations giving zero temperature-frequency coefficient are on

temperature-frequency coefficient is chosen in preference to the angle corresponding to zero inter-mode coupling because at this angle the elastic coupling constant is still very small, whereas at the angle of the AC-cut the temperature-frequency coefficient already has a considerable value.

(i) *AT- and BT-cut Plates*

These have a very low temperature-frequency coefficient over a limited range of temperatures. The fundamental vibration is of thickness shear mode, which makes it possible to clamp the plates rigidly in their holders. Whilst the coupling factors of AT-cut and BT-cut plates are low, they make the use of large dimensional ratios necessary and in practice this limits the application of AT-cut plates to frequencies above 500 kc/s approximately. For frequencies much below this it is difficult to prevent interaction between the thickness shear and other modes of vibration. As stated

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above, the activity of the BT cut is not as great as that of the AT-cut, but the upper frequency limit is higher, due to its higher frequency constant ( $k = 1,630$  for AT and  $2500$  for BT).

In common with the AT and BT cuts, the CT- and DT-cut plates have a very low temperature-frequency coefficient over a limited range of temperatures.

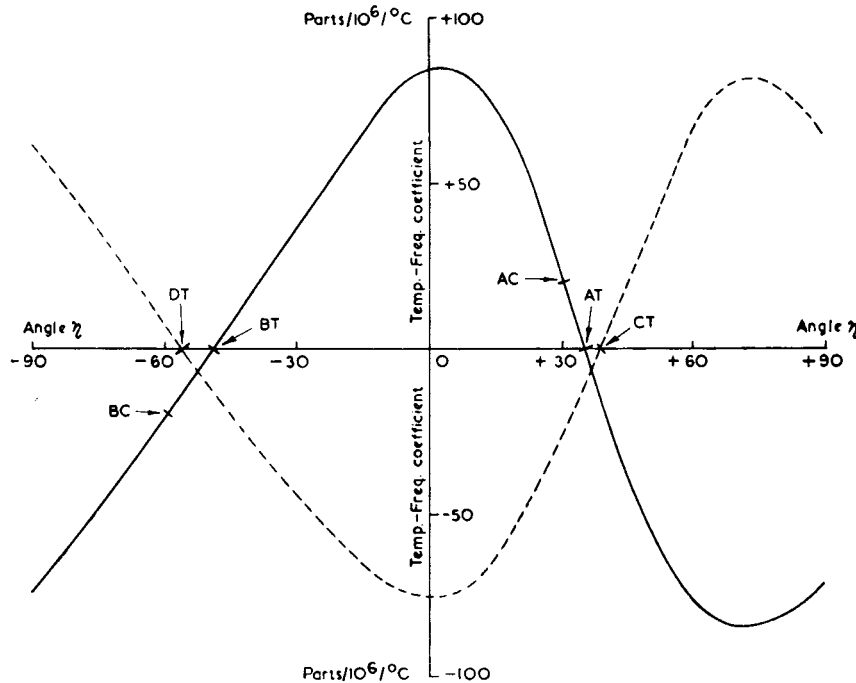


Fig. A.10 Variation of Temperature-frequency Coefficient with Angle of Cut

(ii) *AC- and BC-cut Plates*

These are the cuts which are characterised by zero inter-mode coupling but the temperature-frequency coefficients, positive in the case of the AC-cut and negative in the case of the BC-cut, are large enough to prohibit these plates being used in applications requiring very high frequency stability. They vibrate in thickness shear mode.

(iii) *CT- and DT-cut Plates*

The vibration of CT- and DT-cut plates, while it is of shear mode is not of the simple thickness shear mode of the BT and AT cuts. It is a diagonal shear vibration which is a mode of vibration in which a pair of diagonally opposite corners of the plate move outward while the other corners move inward, and vice versa. Therefore, the frequency determining dimensions of CT- or DT-cut plates are very much larger than those of BT- or AT-cut plates resulting in the former having lower frequencies than the latter. See Fig. A.11.

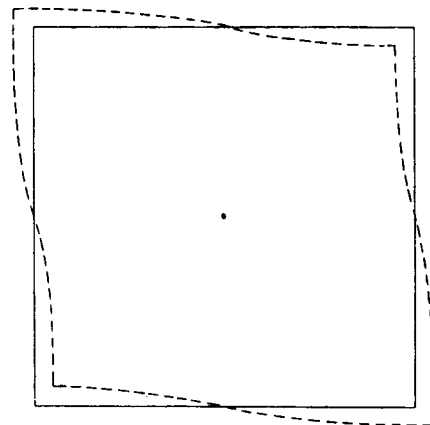


Fig. A.11. Diagonal Shear Mode of Vibration

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CT-cut plates are used for frequencies in the range 200-500 kc/s and DT-cut plates in the range 70-400 kc/s.

#### (iv) ET- and FT-cut Plates

It is possible to utilise overtone vibrations of CT- and DT-cut plates to obtain higher frequencies, but these modes of vibration do not necessarily have a zero temperature-frequency coefficient. Suitable orientations of cut can be found, however, which give zero temperature-frequency coefficient for an overtone vibration. The ET cut provides a plate of zero temperature-frequency coefficient at an overtone vibration

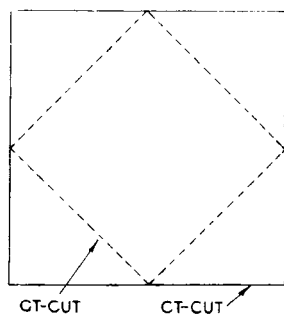


Fig. A.12. GT-cut shown in relation to CT-cut

approximately twice that of a CT-cut plate of the same dimensions. An FT-cut plate is a cut of similar characteristics in which the overtone

range 200-1,000 kc/s and FT-cut plates in the range 140-800 kc/s.

#### (v) GT-cut plates

The cuts so far described in this section are all cuts which are inclined to the Y and Z axes, but not to the X axis. There are, however, certain useful cuts in which there is inclination to all three axes. One of particular interest is known as the GT-cut. It can be considered as being derived from a CT-cut plate, the GT plate being cut from the latter in such a manner that the sides of the GT plate are inclined at  $45^\circ$  to the edges of the CT plate (Fig. A.12). The distinctive characteristic of the GT-cut plate is that it exhibits very small temperature-frequency coefficient over a wide range of operating temperature, e.g.,  $0^\circ\text{C.}$  to  $100^\circ\text{C.}$  The plate vibrates in two coupled extensional modes, one along the width and the other along the length; the former determines the frequency, and the relationship between the two determines the temperature coefficient.

GT-cut plates are used for frequencies in the range 60-1,000 kc/s. They can be clamped at the face centre. The temperature-frequency characteristic of a GT-cut crystal is shown in Fig. A.13.

#### (vi) VW-cut Plates

Another form of cut involves rotation about the X axis (as for the AT, BT cuts, etc.) and in addition a rotation about the Z axis. One of these cuts,

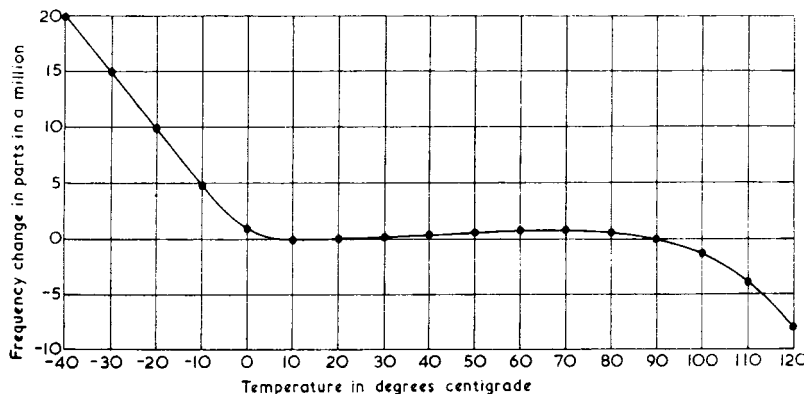


Fig. A.13. Temperature-frequency Characteristic of GT-cut Crystal\*

vibration is approximately twice that of a DT-cut plate of the same dimensions.

ET-cut plates are used for frequencies in the

known as the VW cut, provides a zero temperature-frequency coefficient plate, of the high frequency type, vibrating in thickness shear mode.

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(vii) *MT- and NT-cut Plates*

These cuts are related to the X-cut by a rotation about the X-axis and a second rotation about the length axis of the crystal, the second rotation being greater for the NT cut than for the MT cut. MT-cut plates are used for frequencies in the range 50-100 kc/s and NT-cut plates in the range 4-50 kc/s.

**Equivalent Electrical Circuit of Quartz Oscillator**

A mounted quartz oscillator with contiguous electrodes may be represented, for analytical purposes, by the equivalent electrical circuit shown in Fig. A.14. The elements of this equivalent

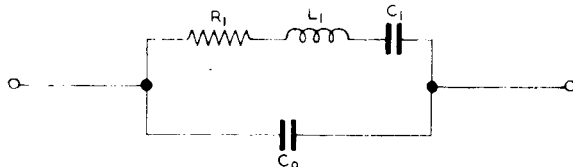


Fig. A.14. *Equivalent Electrical Circuit of Mounted Quartz Crystal with Contiguous Electrodes*

circuit are determined by the mass, elasticity and the system of mounting of the crystal.  $L_1$  is the effective mass and  $C_1$  the elasticity of the crystal transformed into electrical terms;  $C_0$  is the static capacitance, including the stray capacitance of the holder;  $R_1$  represents the internal losses in the crystal, losses at the clamping points and, if the crystal is mounted in air, losses due to the setting up of air waves.

The impedance set up between the terminals by the combination illustrated in Fig. A.14 will be a minimum at the resonant frequency of  $L_1$  and  $C_1$  in series and a maximum at the anti-resonant condition of the entire circuit. In practice the ratio  $C_0/C_1$  is large and consequently there is very small frequency separation between minimum and maximum impedance conditions.

The frequency of oscillation obtained when the crystal unit is connected to a maintaining amplifier is determined not only by the parameters of the crystal unit but also by those of the amplifier. Under conditions of continuous oscillation the reactance of the crystal unit and the reactive component of the impedance presented to it by the amplifier must together total zero. (A crystal will

oscillate only between the resonant and anti-resonant points.) If the reactive component set up by the amplifier across the crystal unit is low the crystal will oscillate at a frequency very close to that producing the minimum impedance condition of Fig. A.14. On the other hand if the reactive component is high the frequency will be very close to that producing the maximum impedance condition.

If the crystal holder has an air gap between crystal plate and electrode the equivalent electrical circuit includes a capacitance  $C_A$ , Fig. A.15, representing the resultant capacitance between plate and electrodes. The capacitance  $C_A$  will affect the oscillation frequency but its value is

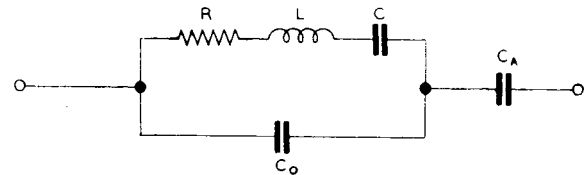


Fig. A.15. *Equivalent Electrical Circuit of Mounted Quartz Crystal when Holder contains an Air Gap or Air Gaps*

large compared with  $C_1$  and its effect will consequently be small.

The  $L$ ,  $C$  and  $R$  values of the equivalent electrical circuit of a quartz oscillator are such as to give a very high  $Q$  value, much higher than that of a high-grade practical LC circuit. The latter might have a  $Q$  value no greater than 200 but G.P.O. Type 6B quartz-crystal units have  $Q$  values between 20,000 and 90,000, and G.P.O. Type W5 units have  $Q$  values of over 60,000.

The phase angle/frequency characteristic of a quartz crystal unit is therefore very much steeper than that of any practical LC circuit.

**Crystal Holders**

The final process in the production of a quartz-crystal oscillator unit is the mounting of the plate between two electrodes in a suitable holder. The type of holder used depends partly upon the frequency stability required and partly upon the mode of vibration of the crystal. Crystal holders used by the BBC may be grouped broadly as (a) holders in which the crystal is clamped, (b) holders in which the crystal is unclamped. Clamped crystals are used in high-stability drive equipments.

