Quartz used in the manufacture of frequency control products is monocrystalline of an asymmetric hexagonal form. Chemically, Quartz is Silicon Dioxide (SiO_2) occurring naturally as the most abundant mineral on earth, constituting approximately 14% of the earth's surface.

For short term accuracy Quartz reigns supreme.

The importance of monocrystalline quartz in the modern electronics industry is the result of its combined properties of piezoelectricity, high mechanical and chemical stability, very high Q at resonance and modern low cost methods of producing extremely high levels of purity in synthetic monocrystalline material.

Quartz is now indispensable as the principal material for controlling frequency in electronic equipment and is only surpassed for long term accuracy by primary atomic standards such as Caesium and Rubidium.

In its basic chemical form silicon dioxide cannot be used for frequency control and must be of the monocrystalline structure in which it exhibits usable piezoelectric qualities due to its asymmetric form.

Piezoelectricity (Greek Piezein 'to press') in monocrystalline quartz was discovered by the Curie brothers at the Sorbonne, Paris 1880.

Piezoelectric materials exhibit a directionally related electric charge when subjected to pressure and conversely the application of an electric charge causes a directionally related force to be generated within the material. The application of an alternating electric field will cause the material to vibrate and subsequently resonate mechanically.The frequency of any mechanical resonance is determined by the physical dimensions of the piece of quartz, the 'cut angle' with respect to the crystalline axis of the original monocrystalline crystal, the ambient temperature and any modifying effects of associated mechanical or electrical components.

There are many piezoelectric materials which could be used for frequency control but amongst these only quartz and tourmaline are of any significance. Crystallised tourmaline is of importance in the field of stress monitoring due to its high output of an electric charge for a given change in applied pressure but its temperature coefficient of frequency is poor and within the field of frequency control it is crystallised quartz which dominates.

The properties of crystallised quartz include its high chemical and mechanical stability and a low temperature coefficient giving a small change in resonant frequency for any change in ambient temperature and a very high Q at resonance. It occurs naturally and all early experimental work was carried out using natural crystallised quartz .

The raw material is still widely mined in Brazil and Madagascar and is used to produce quartz crystals with the highest Q factors. However, naturally occurring crystallised quartz suffers from inclusions of impurities, bubbles, cracks and twinning, which reduce its value for use in frequency control as these reduce the Q factor. Therefore the production of synthetic quartz was established in order to produce a purer form of crystalline quartz.

Synthetic monocrystalline quartz

Synthetic quartz is produced in an autoclave from pieces of crystalline quartz material which are dissolved in an alkaline water solution at approximately 400°C and at a pressure of 1000Kg/cm^2 to produce a super saturated solution.

The process of manufacturing synthetic quartz is known as the hydrothermal method in which prepared seed plates of pre-orientated monocrystalline quartz are suspended in a super saturated solution and by reducing the temperature of the solution the growth of large crystals is obtained under laboratory controlled conditions thus minimising impurities and maximising the useful volume of material. Growth rates of the synthetic material are in the order of 1mm per day or less to achieve a maximum purity.

Quartz resonators for use in electronic circuits are produced by cutting crystalline quartz into wafers(or blanks), plating electrodes onto each side of the wafer and enclosing the resonator into a suitable holder.

The dimensions of the quartz wafer essentially determine the resonator frequency although this is also affected by the size and thickness of the electrodes.

The orientation of the wafer 'cut' to the crystalline optical axis is critical in order to achieve accuracy of the resonant frequency and a necessary low temperature coefficient of frequency for the final resonator unit.

The 'cut' will produce frequency/temperature characteristics which are either second order (quadratic) or third order (ternary) and therefore the characteristics will exhibit single or double turn over points.

The active component

A quartz crystal element is a mechanically vibrating resonant plate cut from monocrystalline quartz with a precise orientation to the crystallographic axis. The physical dimensions of the element and its orientation to the axis will determine in particular the resonant frequency, its initial accuracy and temperature coefficient.

Manufacturers use a number of techniques to measure the resonant oscillation frequency of a quartz element and different techniques are used for high and low frequency elements, it is therefore essential for critical applications that the end user and manufacturer work closely to correlate their measurement methods.

In order to analyse the characteristics of a resonating quartz element, its mechanical resonance is represented, near resonance, by an equivalent electrical circuit with the components L_1, C_1, R_1 and C_0.

Quartz resonators provide a reference frequency with an accuracy far in excess of most industrial and commercial requirements, however, the ultimate stability of any circuit using a quartz resonator as a reference is determined by the environmental conditions and the associated electrical components employed by the end user.

Crystal 'cut'

Figure 1 shows many of the 'cut' orientations, which may be made from a single Z plate quartz crystal, related to the X, Y and Z axis.

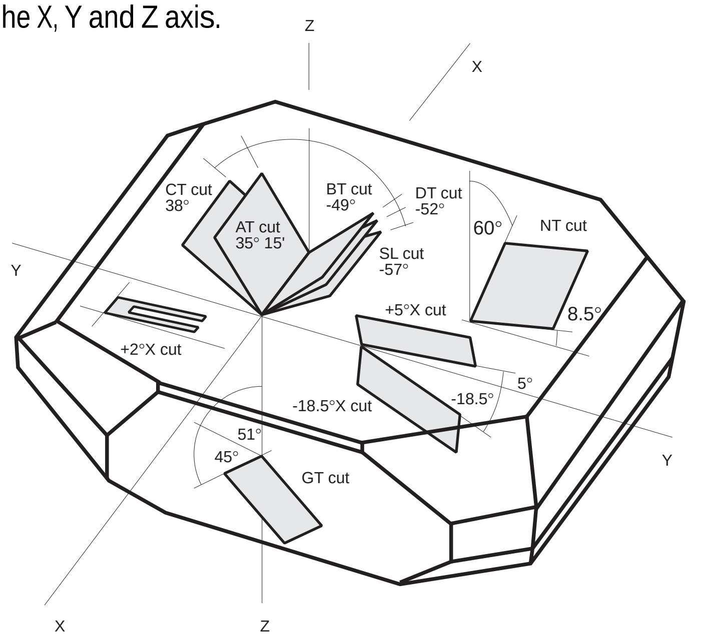

Fig. 1 Cut orientations from a Z plate quartz crystal

The most widely used 'cut' is the 'AT cut', with an orientation of approximately 35°15' to the Z axis, to which elements are generally cut providing resonators with frequencies between 800kHz and 300MHz and excellent frequency/temperature characteristics shown in figure 2.

The 'AT cut' produces a resonator which exhibits very small changes in a crystal resonant frequency for changes in the crystal temperature over a wide temperature range. With two turnover points in the frequency/temperature characteristic the 'AT cut' may be utilised for specialist applications requiring very linear frequency/temperature characteristics over a limited temperature range particularly in the manufacture of TCXO oscillators or for tightly controlled accuracy at the upper turnover point at which the temperature of the crystal would be

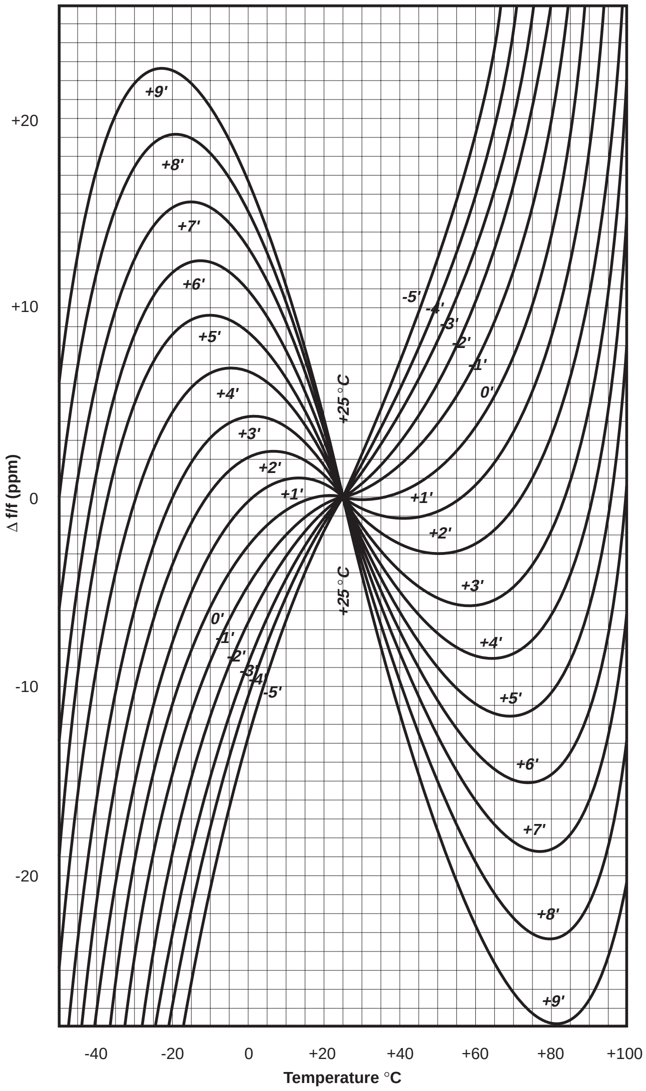

Fig. 2 'AT cut' freq/temperature characteristics

maintained by means of an ovened environment above normal ambient temperature.

For lower frequencies and special requirements a number of 'cuts' may be used depending upon the required characteristics including frequency, temperature coefficient and size, in particular the 'BT cut' is increasingly used for high frequency fundamental designs and is suitable where temperature stability is not demanding. The characteristics of these other cuts generally produce the frequency/temperature curves shown in figure 3.

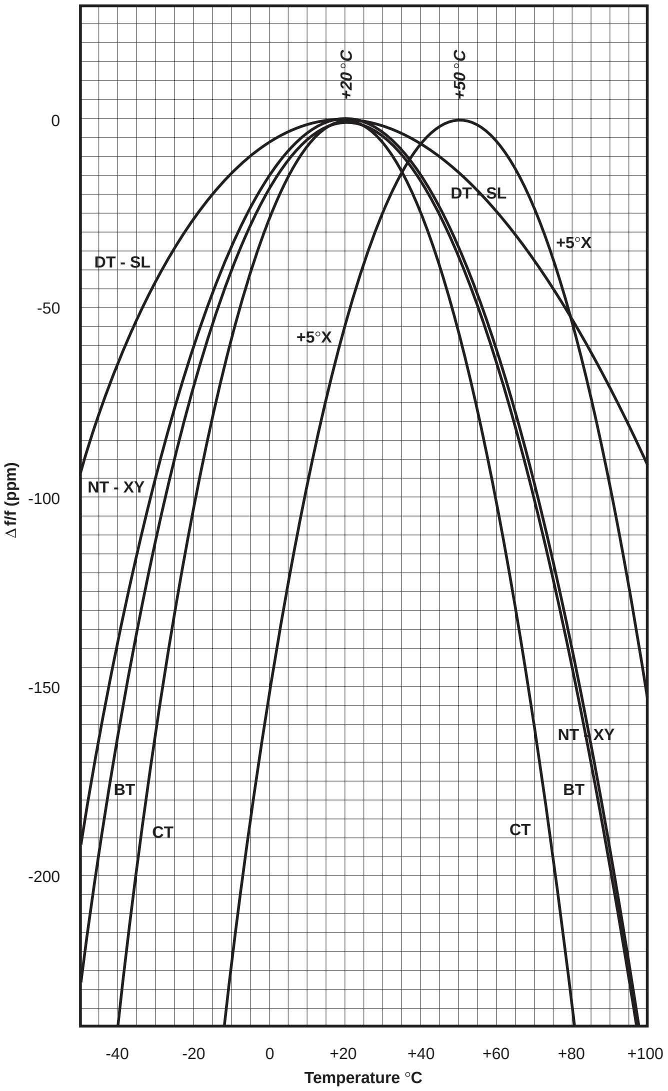

Fig. 3 Second order freq/temp characteristics

Frequency/Temperature characteristics

For a quartz resonator the stability of the frequency with respect to temperature is determined principally by the temperature coefficient of density, the dimensions and elastic modulus of the quartz plate. When the resultant of these three mechanical properties is zero then the frequency/temperature characteristics become optimum and the major design criteria for the manufacturer of quartz resonators is to achieve this optimum over the necessary temperature range. The properties vary considerably with the mode of vibration, type of 'cut' and resonant frequency and figure 2 and figure 3 show comparative frequency/temperature curves for various 'cuts'. The 'AT cut' is significant in that it produces frequency/temperature characteristics at least an order better than other 'cuts' above temperatures of 30°C resulting in its universal use for producing most quartz resonators.

Mode of vibration

The available frequency range of quartz resonators is achieved from different 'cuts' and by utilising various modes of vibration. The approximate C_0/C_1 ratio is of importance where crystal frequencies are to be modulated or pulled in a VCXO circuit, lower ratios of C_0/C_1 allowing greater pulling. The 'AT cut' crystal allows for wide pulling ranges to be achieved with high frequency fundamental crystals providing the highest ranges, the 'BT cut' allows a pulling range approximately half that of the 'AT cut'.

Equivalent electrical circuit

Figure 4 shows a simplified equivalent electrical circuit which represents the properties of a lightly damped mechanical vibrator, such as a quartz resonator, at or near resonance. This circuit is merely a model for the purposes of analysis and the circuit values assume that no other modes of motion are near the particular resonant frequency of the model.

The electrical components of the simplified equivalent circuit represent the following properties:

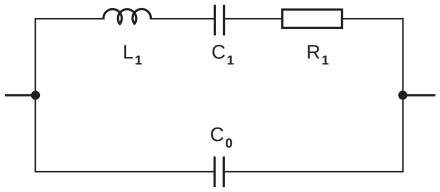

Fig. 4 Simplified equivalent circuit for a quartz crystal resonator

L_1	Motional inductance
C_1	Motional capacitance
R_1	Motional resistance
C_0	Effective shunt capacitance combining electrode and enclosure capacitance

The inductance L_1 represents the vibrating mass of the resonator, the capacitor C_1 its compliance, or elasticity, and the resistor R_1 a combination of internal friction within the element, mechanical losses in the mounting and acoustic losses within the resonating enclosure. The capacitance C_0 is a combined value made up of genuine electrical capacitance between the electrodes and the separate capacitance of the mounting system including capacitance between the crystal holder, wires and case. C_0 can therefore be reduced by earthing the crystal case within its operating circuit.

Two zero phase frequencies evolve from the analysis of the resonator near the point of natural resonance using parameters from the simplified equivalent circuit. These frequencies are designated f_r (frequency at resonance) at which the crystal impedance is very low and f_a(frequency at antiresonance) at which the crystal impedance is very high.

At f_r the crystal is purely resistive and the series resonant condition occurs where the impedance is a minimum and the crystal will pass maximum current. As the frequency is increased, the crystal behaves as an inductive reactance in series with a resistance and finally the parallel resonant condition is reached where the crystal impedance is a maximum and therefore a maximum voltage is developed across the crystal.

$$f_r = \frac{1}{(2\pi\sqrt{L_1 C_1})}$$

$$f_a = \frac{1}{(2\pi\sqrt{L_1 C})} \qquad \text{where} \qquad C = \frac{C_1 C_0}{C_1 + C_0}$$

$$Q = \frac{2\pi f_r L_1}{R_1}$$

The range from f_r to f_a is referred to as the bandwidth of the crystal.

Crystals may be operated either side of f_r by varying the phase condition of the maintaining circuit and the maximum possible 'pulling' either side of f_r will be inversely proportional to the ratio C_0/C_1.

The impedance of the resonator is minimum for the series resonant condition f_r and maximum for the parallel antiresonant condition f_a. The ESR (effective series resistance) is measured at f_r where the crystal reactances cancel and the element appears purely resistive.

Figure 5 shows the impedance characteristics of a quartz crystal resonator for conditions close to resonance. In practice the operating frequency of a parallel resonant crystal is an intermediate point between f_r and f_a which is generally given the symbol f_0.

The extent to which the resonant frequency may be varied between f_r and f_0 is known as the pulling range of the crystal and this is inversely proportional to the ratio C_0/C_1 which may to some extent be controlled by the crystal manufacturer. The ratio of C_0/C_1 is much greater

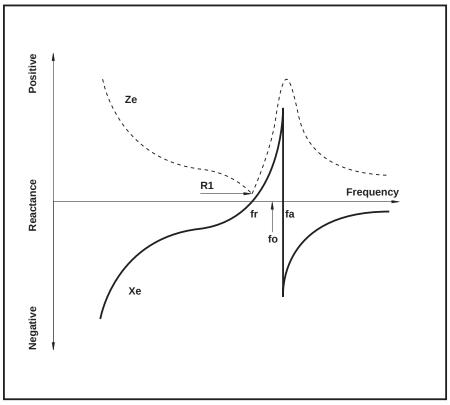

Fig. 5 Frequency/impedance characteristics of a quartz crystal resonator close to resonance

for crystals operating in their overtone mode and the pulling range is reduced by a factor of approximately n^3 where 'n' is the order of the overtone. The pulling range of a crystal is mostly dependent upon the circuit conditions.

Crystal frequency/Load characteristics

Figure 6 shows the change in operating resonant frequency from loading a crystal with either a series or parallel capacitive load reactance.

The crystal frequency may be "pulled" by using a reactive element in the load circuit. This element may be inductive or capacitive and may be incorporated to remove the crystal adjustment tolerance or in phase locked loop or frequency modulation applications.

A capacitive element is the most widely used to pull the crystal frequency and the following equations illustrate the theoretical pulling range of the crystal but circuit conditions and in particular series inductance and stray capacitance have a considerable effect upon the pulling range and must be carefully considered.

The capacitive load may be connected in series with the crystal for operation in the low impedance condition or in parallel with the crystal for operation in the high impedance condition. The resulting approximate frequencies are then:

$$f_0 \cong f_r \left[1 + \frac{C_1}{2(C_0 + C_L)} \right]$$

OR

$$\Delta f / f_r = \frac{C_1}{2(C_0 + C_L)} \qquad \text{where} \qquad \Delta f = f_0 - f_r$$

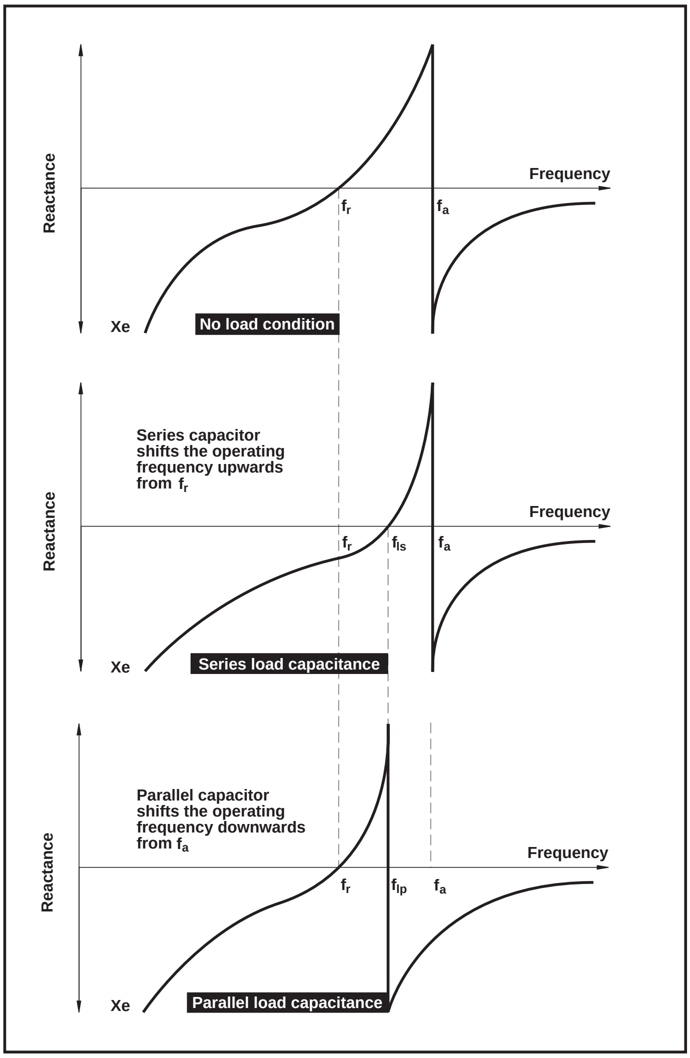

Fig. 6 Change in operating resonant frequency for series or parallel capacitive load reactance

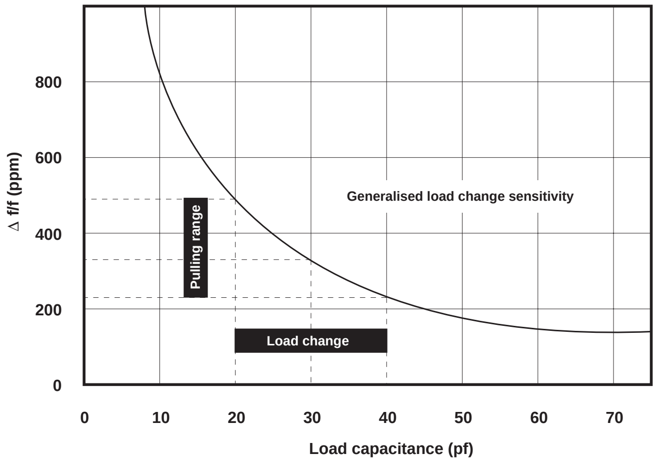

Fig. 7 Characteristics of crystal frequency against load capacitance.

Drive level

It is essential to operate crystals with the drive level for which they were designed. The frequency of all crystal units is dependent upon drive level and excessive drive levels can cause an irreversible frequency change. A drive level above the manufacturers specification will increase the frequency and a low drive level will decrease the frequency.

High drive levels excite unwanted modes of vibration, cause serious degradation of the frequency temperature characteristics and shift the frequency due to overheating of the resonator.

Low drive levels cause an increase in the ESR and may result in oscillator start up problems.

Effects of crystal aging

Aging is the change in crystal frequency with time. The most important result of aging is the change of resonant frequency due to many complex physical changes including the change in vacuum conditions within the enclosure, a gradual strain relief within the crystal blank, matter transfer from particles of the crystal blank and changes in material interfaces.

Contamination within the crystal enclosure also has a major effect on the aging rate and the following summary shows comparative rates of annual aging which may be expected from using different case materials and methods of encapsulation.

Sealing method	*Annual aging*	*Package*
Solder seal	±10ppm	HC-18
Resistance weld	±3ppm	HC-49
Cold weld	±1ppm	HC-43
Glass seal	±0.5ppm	HC-26

The very poor aging rates associated with the old solder seal method precludes the use of this type of sealing in all but the most basic of applications, although it persists in the manufacture of crystal filters, and modern methods of resistance weld sealing have all but replaced the solder seal with a far superior aging rate and almost no cost penalty.

Cold weld and glass weld enclosures are used in applications where high long term accuracy is mandatory.

Aging for 'AT cut' crystals may increase or decrease the crystal frequency and this direction of change is not accurately predictable, aging for low frequency cuts, producing second order quadratic functions of temperature coefficient, will generally increase the frequency.

Unwanted spurious response

All resonating quartz plates produce a fundamental response and also natural responses at the overtones of the fundamental frequency. With correct circuit design the loop gain at the desired frequency is maximised and the unwanted natural resonant modes rarely cause problems.

However a spurious response close to the desired response can cause serious problems with an oscillator starting up at the wrong frequency or shifting to the wrong frequency during operation at temperature extremes or perhaps where the resonator is being pulled in a VCXO application.

High drive levels and the imposition on the crystal manufacturer of unnatural C_1 values are the major causes of unwanted crystal responses.

Where the spurious response must be minimised in critical applications it should be specified as a minimum resistance within the frequency range over which it applies.

Mechanical reliability

The most rugged crystal units are the medium to high frequency 'AT cut' units where the mass of the crystal blank is a minimum and they may be mounted quite rigidly without severely affecting the necessary mechanical vibration. Cuts such as 'CT', 'DT', and 'X' used for producing lower frequency units are less robust due to their necessarily weaker mounting systems.

All crystal units will exhibit changes in frequency and resistance when subjected to mechanical stress and under severe conditions the specified electrical performance may have to be relaxed and the unit may require protection by design of its mounting within the overall equipment to prevent permanent damage.