

Monocrystalline quartz

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.



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 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.

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.

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.

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.

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

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/cm² 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, C, R and C₀.

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.

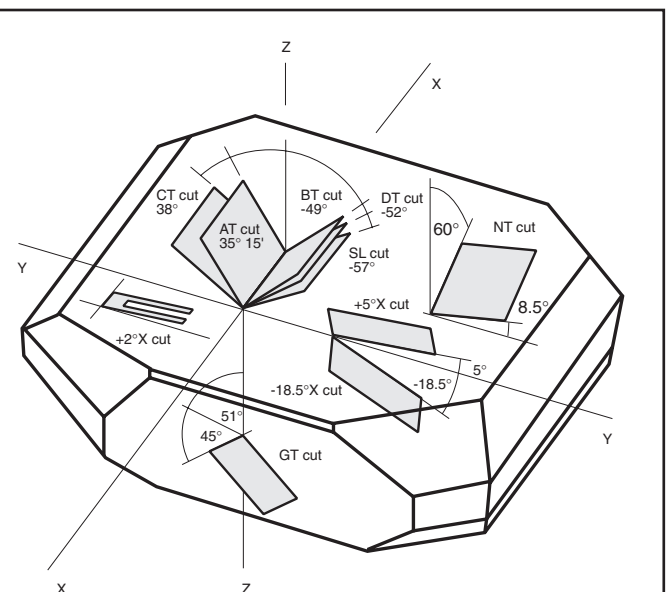


Figure 1 Cut orientations from a Z plate quartz crystal

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.

The most widely used 'cut' is the 'AT cut', with an orientation of approximately 35° 15' to the Z axis, providing resonators with frequencies between 800kHz and 300kHz 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 maintained by means of an ovened environment above normal ambient temperature.

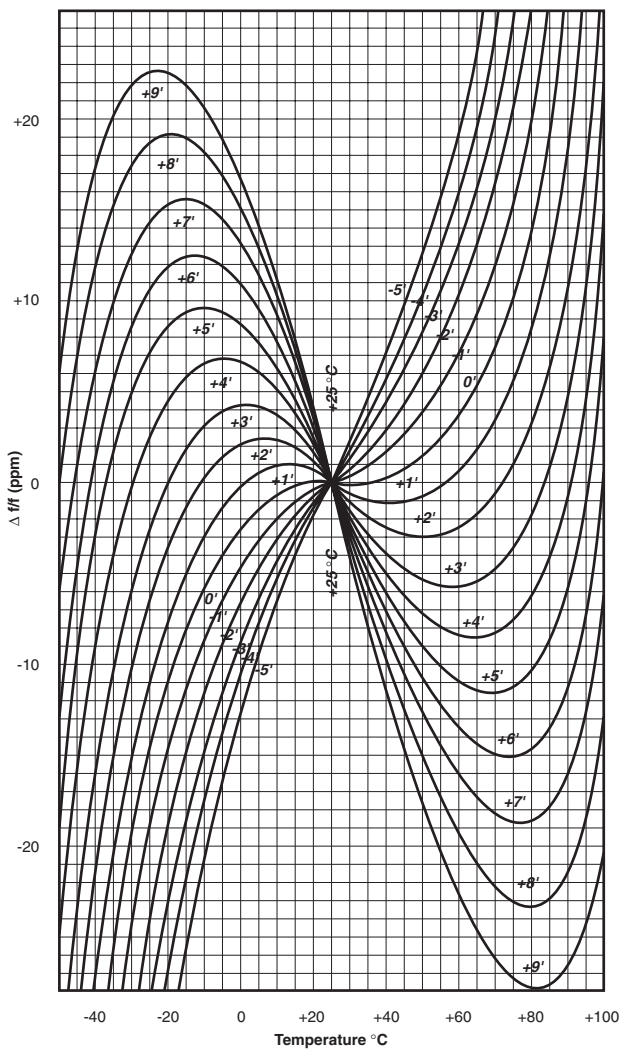


Figure 2 AT cut frequency / temperature characteristics

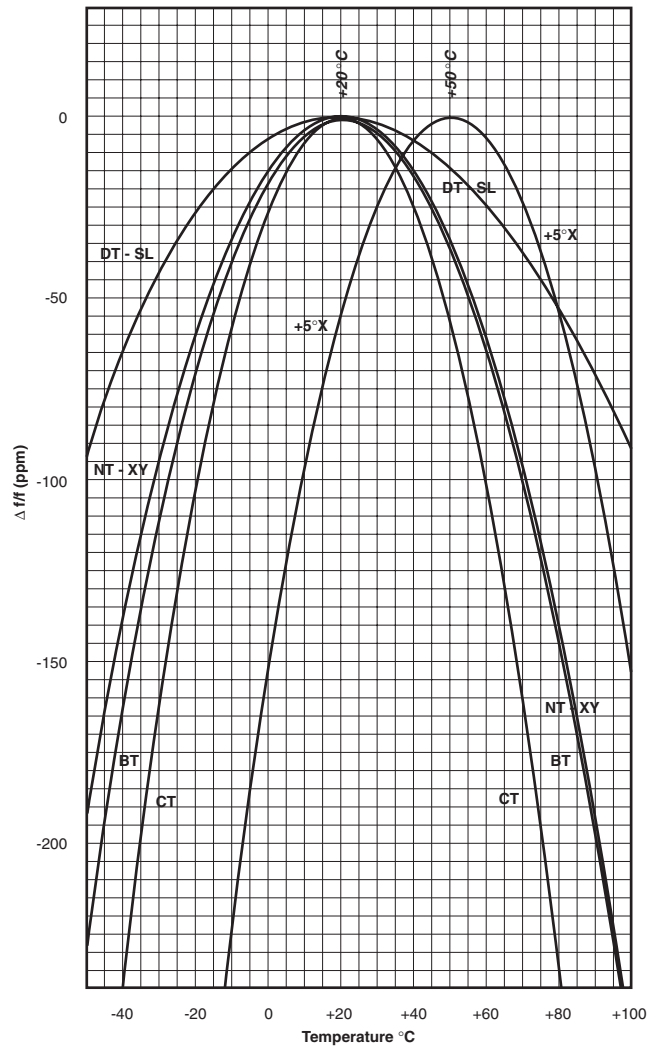


Figure 3 Second order frequency / temperature characteristics

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.

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 the 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 temperature 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:

- 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 capacitors C_0 is a combined value made up of capacitance between the electrodes and also that 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.

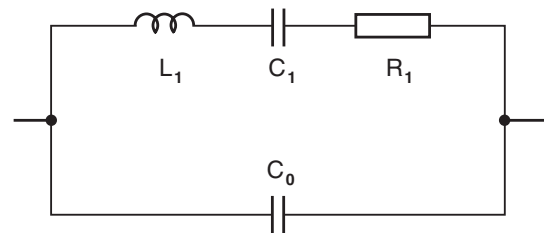


Figure 4 Simplified equivalent circuit for a quartz crystal resonator

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 as 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.

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

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

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

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 reactance 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_o

The extent to which the resonant frequency may be varied between F_r and F_o 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.

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.

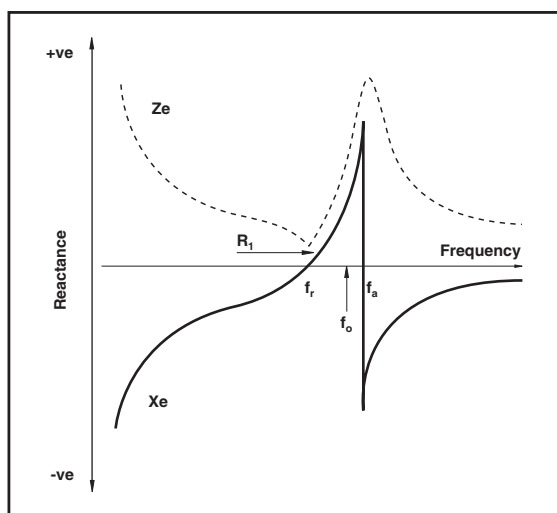


Figure 5 Frequency / impedance characteristics for a quartz crystal resonator close to resonance

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 modulations 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:

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

OR

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

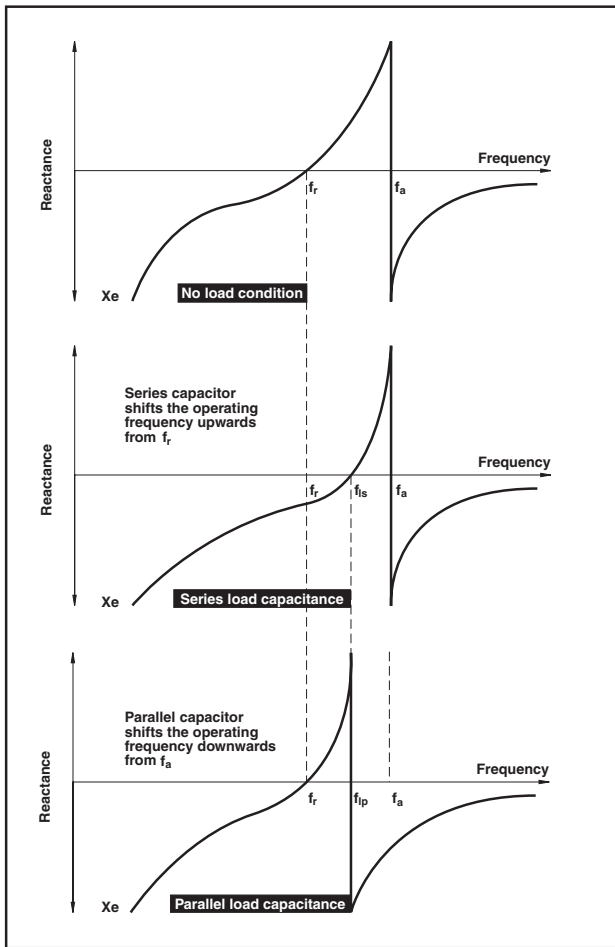


Figure 6 Change in operating resonant frequency for series or parallel capacitive load reactance

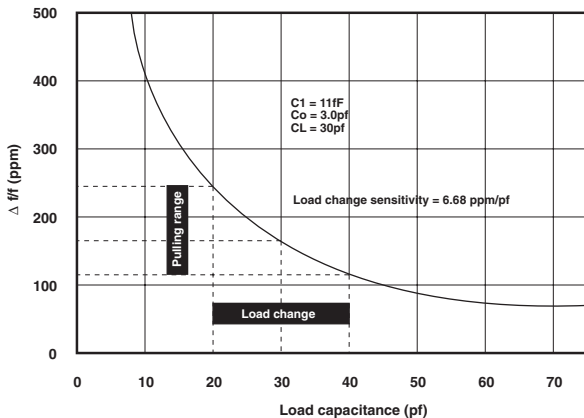


Figure 7 Characteristics of crystal frequency against load capacitance

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 ageing

Ageing is the change in crystal frequency with time. The most important result of ageing 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 and its supports, 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 ageing rate and the following summary shows comparative rates of annual ageing which may be expected from using different case materials and methods of encapsulation.

Sealing method	Annual ageing	Package
Solder seal	+/-10ppm	HC-18
Resistance weld	+/-2ppm	HC-49
Cold Weld	+/-1ppm	HC-43
Glass seal	+/-0.5ppm	HC-26

Cold weld and glass weld enclosures are used in applications where high long term accuracy is mandatory. Ageing for 'AT cut' crystals may increase or decrease the crystal frequency and this direction of change is not accurately predictable. Ageing 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.

General

Quartz crystals may be specified with each parameter precisely identified within tight tolerance and for the most critical applications this may be necessary and the inevitably high cost justified.

However, for the majority of applications only a limited number of mandatory parameters need to be specified allowing the crystal manufacturer to apply standard established production techniques and methods to provide quartz crystals at a reasonable cost. For this abbreviated method of specifying crystals it is important that the application of the crystal should be stated since certain applications such as 'ovened crystals' or VCXO crystals' are then identified and therefore manufactured accordingly to provide the necessary specific performance. The method eliminates ESR, drive level, spurious response, cut and pulling requirements and therefore where these are important, due to the application, they cannot be ignored.

Mandatory requirements

1. Frequency (fundamental, overtone)
2. Enclosure
3. Calibration tolerance at +25°C
4. Temperature tolerance
5. Temperature range
6. Load condition (series or parallel pF)
7. Application

Frequency

The frequency of a crystal is usually specified in MHz for units of 1.0MHz and above and kHz below 1.0MHz. The fundamental or overtone mode required should be stated and the following table indicates the general limits for each mode:

Fundamental mode	~ 155MHz
3rd overtone	(20 - 75)MHz
5th Overtone	(50 - 150)MHz
7th Overtone	(125 - 175)MHz
9th Overtone	(150 - 225)MHz

Crystal enclosures

Size of enclosures is often important in circuit board design but if a quartz resonator is to be supplied in the smallest possible enclosure there may be inevitably be a trade off against many other parameters in particular ESR, temperature coefficient, drive level and spurious response.

Modern resistance weld enclosures provide a good compromise between cost and quality and the MIL spec HC-49 enclosure is the most widely used. There are enclosures of glass, metal and plastic with glass used for either low frequency units or where minimum aging rates are required and plastic for very low cost including the enclosing of ceramic resonators.

Ceramic surface mount crystal packages are increasingly used in volume applications and provide low profile units and specifications to replace many metal case types.

There are three methods used to seal crystal units in metal cases, solder seal, resistance weld and cold weld, each method of sealing is summarised as follows:

Cold Weld - Case sealed using pressure to weld the metal faces, almost no internal pollution, excellent aging, high quality, very good seal, expensive.

Resistance Weld - Case sealed using heating effect of electric current through steel case, low internal pollution, very good aging rate, good quality, good seal, reasonable cost.. This is the most widely used method of sealing for general purpose crystals.

Solder seal - Case sealed using pre-tinned faces and flow soldering or hand soldering to achieve a seal, the case is then further filled with an inert gas and totally sealed using solder. Very poor aging, lowest cost, low quality, high internal pollution and initial thermal shock.

Calibration tolerance, Adjustment tolerance

Specified in ppm (parts per million) generally at +25°C the calibration tolerance is a deviation in crystal frequency due to manufacturing tolerances. It is a constant which may be adjusted out during the setting up of the maintaining circuit and therefore is often referred to as the adjustment tolerance.

Temperature tolerance, Temperature coefficient and temperature range

Of all variables the temperature tolerance is perhaps the most important since the selection of monocrystalline quartz to manufacture the resonator was made on the basis of its extremely good temperature coefficient of frequency.

A significant part of the cost of any quartz crystal relates to the required temperature tolerance and it must therefore be specified as necessary and not over-specified. This cost factor relates to the very high accuracy of cut necessary to achieve low temperature tolerances.

Temperature tolerance is specified in ppm over a temperature range which is itself usually symmetrically specified either side of +25°C, e.g. (0+50)°C, (-20+70)°C etc.

Crystals used in ovened applications have a controlled ambient temperature which is matched by the crystal manufacturer to the high turnover point of the crystal temperature characteristics. At this point the characteristics exhibit a zero gradient and very high accuracy can be obtained from the use of an oven with good temperature control.

Load condition

The circuit load condition of either series resonance or parallel resonance must be known for the correct operation of the quartz resonator.

If the resonator is operating at a low impedance state this corresponds to the series resonant condition, the load capacitance is effectively infinite, and the load is 'series'.

If the resonator is operating at a high impedance state this corresponds to the parallel resonant condition and a finite load capacitance must be specified in order to allow the crystal manufacturer to correlate the load conditions for operation at the correct frequency, this load condition is 'parallel' and is always specified in pF.

For parallel resonant crystals operating at high fundamental frequencies it is critical that the load capacitance is specified within 0.5pF of the actual circuit value for correct correlation.

The standardised values of parallel load capacitance are 12pF, 20pF and 30pF.

Application

The most infrequently specified parameter for quartz crystals is the application and this most important parameter may be vital in designs where the crystal manufacturer is being asked to produce a resonator for use in specific applications such as an oven, VCXO, TCXO or in a particularly hostile environment.

Supplementary requirements

1. Drive level
2. ESR
3. C_o
4. C_1
5. L_1
6. Cut
7. Q
8. Insulation resistance
9. Pullability
10. Spurious response
11. Perturbations
12. Aging
13. Pre-aging
14. Vibration
15. Shock
16. Storage temperature

Of the supplementary requirements only those which directly affect the application of the quartz crystal should be specified. The majority of these requirements will have been considered by the manufacturer of the crystal if the application is specified in the mandatory requirements.

Over-specifying a crystal will adversely affect the cost and availability and could have a detrimental affect on the mandatory requirements which may have to be traded against less important criteria.