Quartz used in the manufacture of frequency control products is mono crystalline 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.

The significance of mono crystalline 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 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.

Nevertheless the recent development of mems, micro electro mechanical systems, and nems, nano electro mechanical systems, is set to revolutionize the frequency control market with the integration of simple clocks into the silicon substrates used for IC fabrication.

These miniature devices may inevitably replace all simple clocks providing added reliability at lower cost and where minimum timing accuracy is a requirement.

In its basic chemical form silicon dioxide cannot be used for frequency control and must be of the mono crystalline structure in which it exhibits usable piezoelectric qualities due to its asymmetric form. Piezoelectricity (Greek Piezein 'to press') in mono crystalline quartz was discovered by the Curie brothers at the Sorbonne, Paris 1880.

However it was not until 1917 that this property was utilized in a practical application when professor Langevin in France and A.M. Nicolson at Western Electric independently designed sonar transceivers for the detection of submarines at sea.

Nicolson later went on to file a number of patents for applications using both quartz and Rochelle Salt. This latter material responded strongly to sound waves and electrical stimulus and was incorporated by Nicolson into designs for Microphones, Loudspeakers and Phonograph pick-ups. While Nicolson had proposed the use of Piezo electric materials for controlling the frequency of a vacuum tube oscillator it was Dr. Walter Cady of the Wesleyan University who filed the first patents for crystal controlled oscillators in 1923.

Prof. G. W. Pierce of Harvard University carried out further work on crystal oscillator development at about this time. Pierce's main achievement was the design of a crystal controlled oscillator using only one vacuum tube and no tuned circuits other than the crystal itself.

During the early 1920's crystal oscillator development and radio technology progressed steadily side by side. The major applications for crystal oscillators during these early days was for use as time standards and it was not until around 1926 that crystal oscillators were used to control the frequency of a radio transmitter. This was done at radio station WEAF in New York which was owned by AT and T.

Bell Telephone Labs who were part of AT&T and along with The Marconi Company in the U.K. and S.E.L. Germany achieved many significant developments in crystal technology during the 1930's. In 1934 Messrs. Lack and Willard at Bell Labs discovered the AT Cut and BT Cut crystals which gave the communications industry vastly

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improved frequency vs temperature performance crystals.

Improved sealing and production techniques along with the discovery of a new family of Stress Compensated cuts are among some of the advances that have been made during the last decade together with the more recent inverted mesa process and miniaturisation of crystals and oscillators.

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 mechanically resonate. The frequency of any mechanical resonance is determined by the physical dimensions of the material, the 'cut angle' with respect to the crystalline axis of the original mono crystalline crystal, the ambient temperature and any modifying effects of associated mechanical or electrical components.

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

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 pure form of crystalline quartz free from twinning and impurities.

Synthetic quartz is produced in an autoclave from a saturated solution of S_iO_2 *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 mono crystalline quartz are suspended in the 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 and the associated electrical circuitry.

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 mono crystalline 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. The orientation of the cut angle to the *crystallographic axis may be a single orientation as in the AT Cut or a doubly rotated orientation as in the SC Cut.*

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.

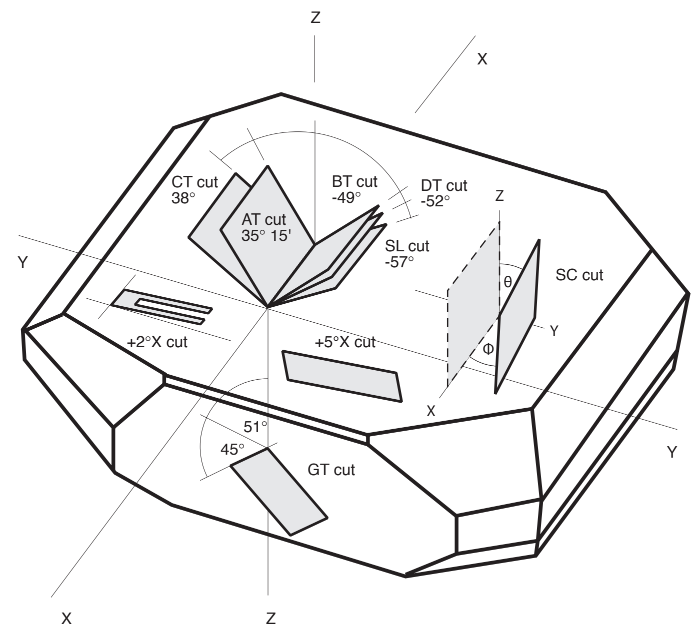

Fig. 1 Cut orientations from a Z plate quartz crystal

The specific accuracy of a quartz crystal resonator is achieved by precise cutting of angles orientated to the crystallographic axis. These axis are referred to the Z axis which is the optical axis of the crystal. many cuts have been developed including AT, IT, BT, FC and SC and each has particular advantages in resonator applications.

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 the excellent frequency/temperature characteristics shown in figure 2.

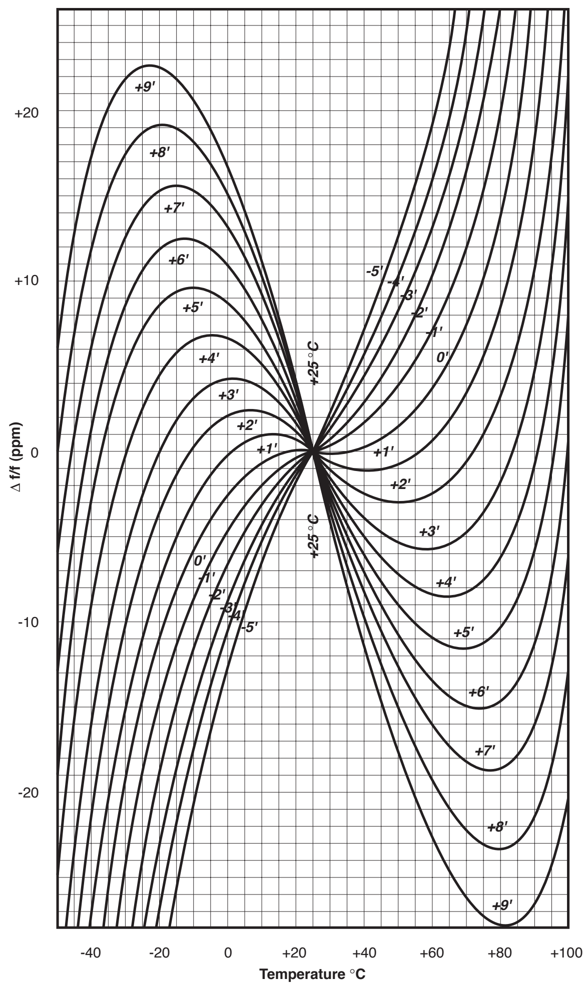

Fig. 2 'AT cut' freq/temperature characteristics

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. 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.

SC cut crystals are used almost exclusively in precision OCXO designs. They are from a family of double rotated cuts, related to the crystallographic axis, and are relatively expensive to produce.

Compared with the AT cut they exhibit lower ageing, lower sensitivity to shock and vibration and G sensitivity and much better phase noise performance. They can also be heated to the working oven temperature much faster, with no degradation in performance, due to their stress compensated doubly rotated design.

The SC cut also produces a higher natural turnover temperature coefficient compared with the AT cut and modified SC cuts have increased this to above 100°C making the SC cut ideal for high temperature OCXO applications.

Disadvantages of the SC cut include relatively higher cost, and lower pullability, the latter precluding their use in VCXO oscillator designs.

Crystal applications for VCXO have been extended with the inverted mesa process that utilises chemical etching to produce an extremely thin resonating centre section of an AT cut crystal blank supported by a thicker peripheral edge, the thin centre section, necessary for high frequency fundamental resonance, being too fragile to survive unsupported. Inverted mesa crystals increase fundamental resonance beyond 250MHz and thus provide a very wide pulling range for VCXO designs.

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.

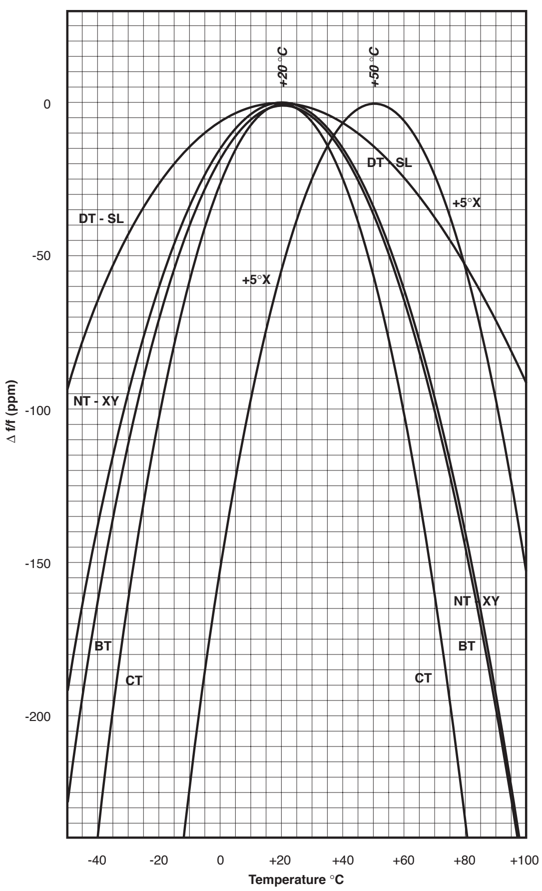

Fig. 3 Second order freq/temp characteristics

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 vs temperature characteristics at least an order better than other 'cuts' above temperatures of +30°C resulting in its historically universal use for producing the majority of quartz resonators used in many standard applications. However the development of the SC cut now provides crystal characteristics which dominate the production of high quality precision OCXO oscillators exhibiting low ageing, high accuracy and excellent phase noise particularly for the for the telecomms, datacomms and instrument industries.

Figure 4 and figure 5 show the frequency vs temperature curves for the SC cut.

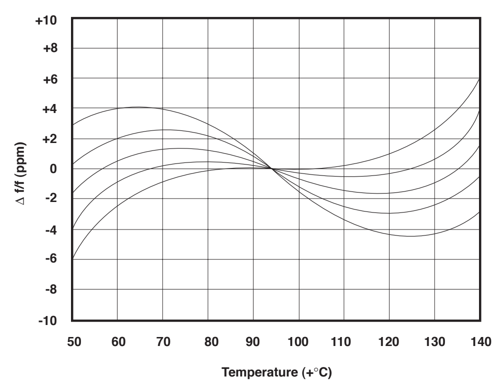

Fig. 4 Low temp. SC cut characteristics

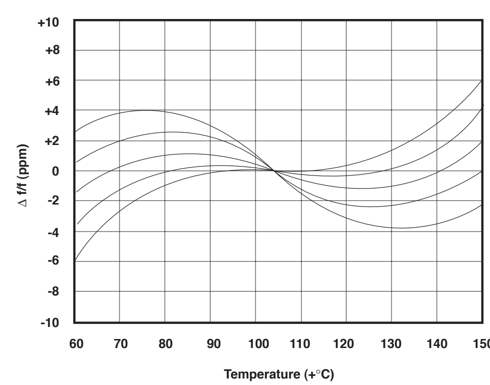

Fig. 5 High temp. modified SC cut characteristics

Mode of vibration

The available frequency range of quartz resonators is achieved from different 'cuts' and by utilising various modes of vibration. The approximate C0/C1 ratio is of importance where crystal frequencies are to be modulated or pulled in a VCXO circuit, lower ratios of C0/C1 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 6 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.

In the special case of the SC cut however there are close in modes which do need special consideration and which must to be suppressed when designing the supporting electronic circuit. These do not however affect the basic simplified circuit equations.

The electrical components of the simplified equivalent circuit represent the following properties:
L_1 C_1 R_1 C_0

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

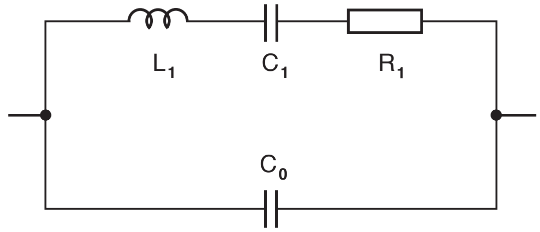

Fig. 6 Simplified equivalent circuit for a quartz crystal resonator

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 anti-resonance) 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.

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

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

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

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 fr 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 7 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 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.

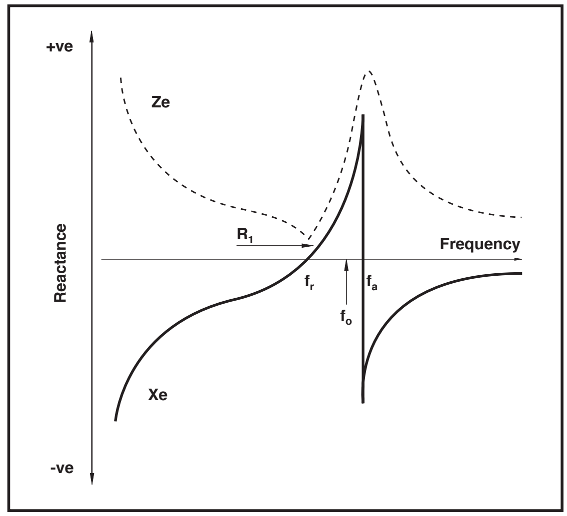

Fig. 7 Frequency/impedance characteristics of a quartz crystal resonator close to resonance

Crystal frequency/Load characteristics

Figure 8 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.

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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

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

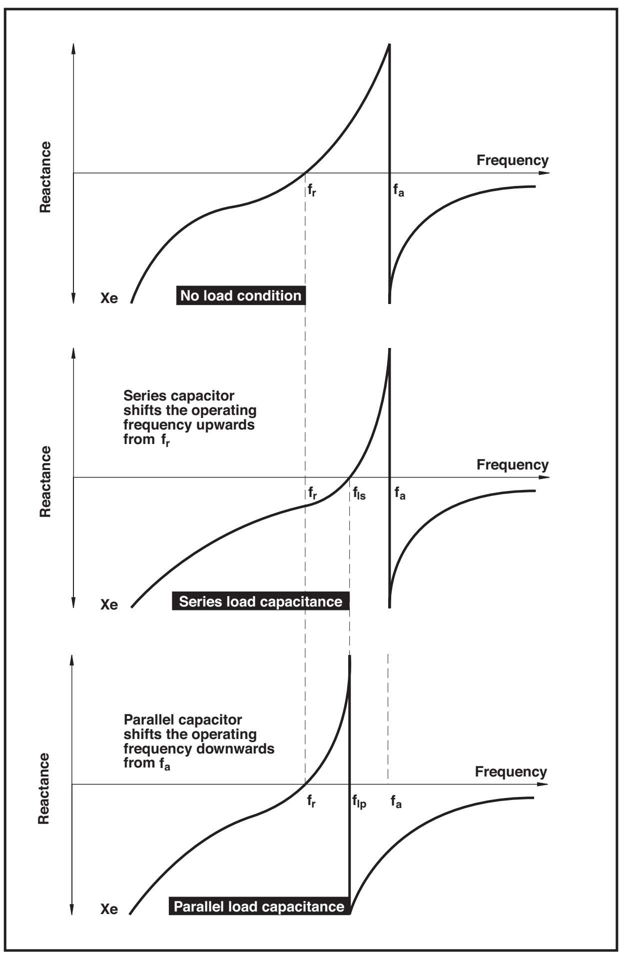

Fig. 8 Change in operating resonant frequency for series or parallel capacitive load reactance.

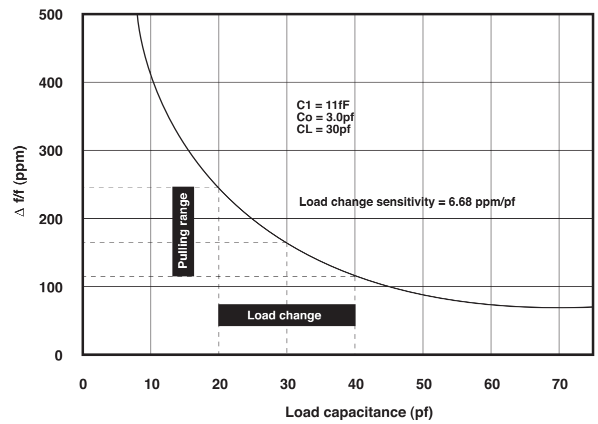

Fig. 9 Characteristics of crystal frequency against load capacitance.

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.

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Effects of crystal aging

Aging is defined as the change in crystal frequency over 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 an 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 ageing	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 dated 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. 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 and modern high temperature vacuum brazed sealing produces excellent long term aging in otherwise correctly prepared units.

Aging 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.

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Mechanical reliability

Rugged crystal units are manufactured from 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.

However the SC cuts are less sensitive to G forces and produce less spurious response from shock and vibration and when mounted in three or four point systems realise the highest mechanical reliability.

Miniature smd designs have low mass and therefore good shock and vibration performance although the very best high shock survival is exhibited by the macro miniature mems and nems designs with survival rates up to 30,000G.

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 careful design of mounting and orientation within the overall equipment to prevent permanent damage.

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