Understanding Quartz Crystals

The usage and applications for quartz crystal devices is increasing with each new technological advancement in computers and peripherals, consumer electronics, telecommunications, and industrial electronics. More and more engineers are now responsible for specifying crystal parameters for their specific application. Along with this new responsibility comes the need to better understand crystal devices. This Engineering Note will attempt to take away some of the mystery in trying to define certain parameters for crystals.

I. Quartz and Its Properties

The quartz crystal or resonator operates due to the piezoelectric effect. The piezoelectric effect of quartz allows it to produce an electrical charge on its surface when the same surface(s) are distorted or subjected to pressure. This distortion allows the crystal to vibrate at a particular resonant frequency. Conversely, the application of an alternating voltage produces the same type of mechanical vibration.

Quartz is one of several forms of silicon dioxide (SiO_2) that is found in nature; mostly in Brazil. Natural quartz is costly to mine. Consequently, most of the quartz used for crystal fabrication today is of the "cultured" or synthetic variety. Cultured quartz is produced by placing small seeds of quartz mixed with an alkaline solution in an autoclave. This mixture is subjected to high heat (> 400°C) and high pressure (30,000 psi). This causes the quartz to dissolve and reform as thin slices of quartz. This process takes approximately 30-45 days.

Quartz is ideal for use as a frequency determining device because of its predictable thermal, mechanical, and electrical characteristics. The quartz crystal is one of the few devices that can provide a high-Q (quality factor) that is needed for precise frequency control in oscillators used as a timing standard.

II. Vibrational Modes and Orientation Angle

There are many different vibrational modes for crystals as shown in Figure 1. The frequency versus temperature characteristics of quartz crystal are primarily determined by the orientation angle at which the quartz wafers are cut from a given bar of quartz. These properties are dependent on the reference directions within the crystals. These directions are referred to as "axes".

There are three axes in quartz, the X, the Y and the Z. An ideal crystal would consist of a hexagonal prism with six facets at each end. See Figure 2. A cross section taken from that prism would look like the depiction in Figure 2.
The Z-axis is known as the "optical" axis and repeats its physical properties every 120° as the crystal is rotated about the Z-axis. The X-axis is parallel to a line bisecting the angles between adjacent prism faces.

This axis is called the "electrical" axis. Electrical polarization occurs in this direction when mechanical pressure is applied. An XT-cut crystal is produced from a slab of quartz cut from that portion of the quartz bar that is perpendicular to the X-axis. The XT-cut crystal if often referred to as a "tuning fork" crystal and is used extensively for 32.768 kHz crystals such as the M-tron MMCC-1, MMCC-2, and SX1555. The frequency vs. temperature for the XT-cut crystal is shown in Figure 3
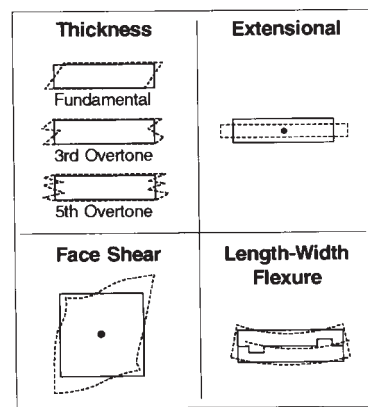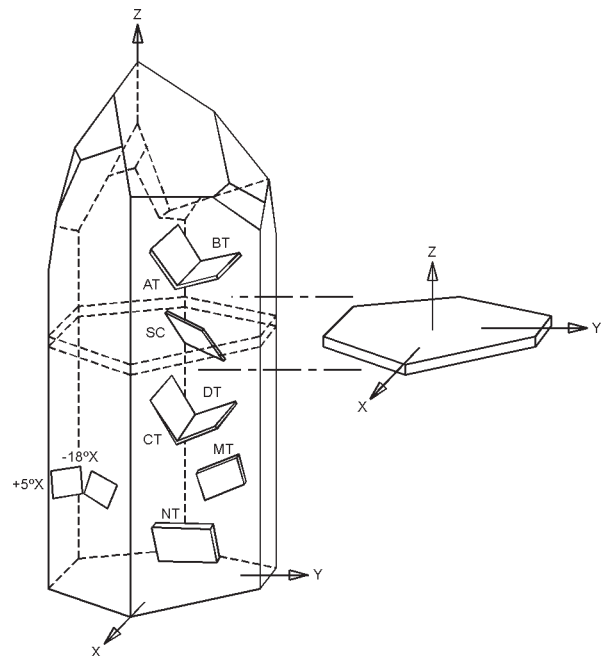(Page 143).

Figure 1

Figure 2

Temperature (ºC)

Figure 3

TYPICAL TEMPERATURE CHARACTERISTICS

The crystal has electrodes deposited on both sides. These electrodes are made of a low resistance metal such as silver, gold and aluminum. The electrode structure allows for an electrical voltage to be applied to the crystal in order to produce mechanical vibration. The electrode also provides a means of attaching the crystal to the mounting structure of the crystal base. See figure 5.
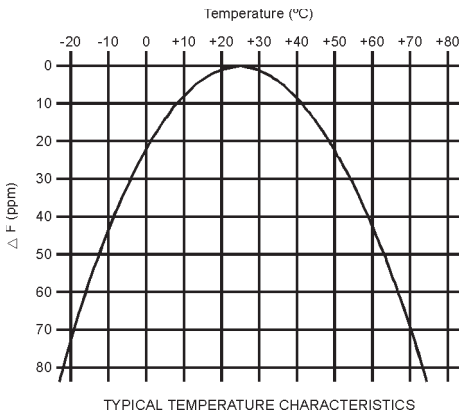
Figure 5

The Y-axis, which is also known as the "mechanical axis", runs at right angles through the face of the prism, and at right angles to the X-axis. Most Y-axis crystals vibrate in their "sheer modes"; face shear for low frequency CT and DT cut crystals, and the thickness shear for higher frequency AT and BT cut crystals.

The AT cut is the most popular of the Y-axis group because of its excellent frequency vs. temperature characteristics. The AT cut is produced by cutting the quartz bar at an angle of approximately 35° 15' from the Z-axis. Figure 4 shows the frequency vs. temperature characteristics for AT-cut crystals.
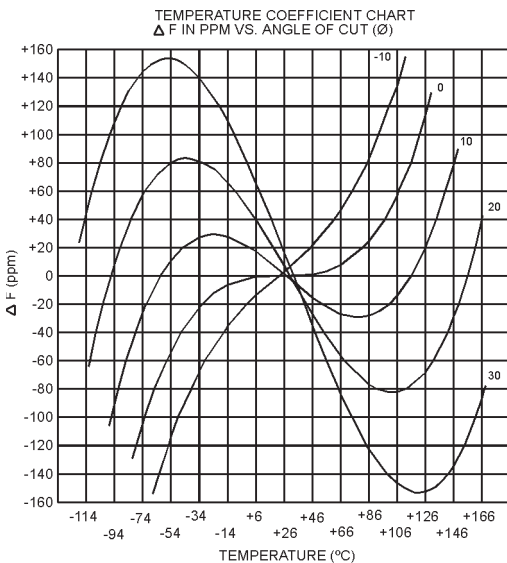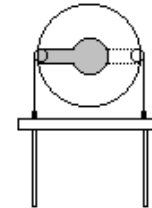
TEMPERATURE COEFFICIENT CHART
Δ F IN PPM VS. ANGLE OF CUT (Ø)

Figure 4

TEMPERATURE (ºC)

The crystal resonator is usually a round disc. The thickness (d) of the disc is related to the fundamental mode frequency (f) by the equation:

$$f \text{ (kHz)} = \frac{N}{d(mm)}$$

Where N = 1660 kHz x mm

Because the frequency of the crystal is related to its thickness, there is a limitation in the manufacturing of high frequency fundamental crystals. The higher the frequency, the thinner the crystal blank.

Losses in manufacturing for these high frequency crystals usually stem from breakage during lapping and mounting. These losses result in lower yields and consequently a higher price crystal.

Fundamental frequencies up to 35 MHz are attainable using standard crystal designs and processes. For frequencies above 35 MHz overtone modes or fundamental inverted mesa crystals are recommended. With overtone modes only odd number harmonics or multiples can be generated. Fundamental inverted mesa designs up to 500 MHz are possible.

Normal overtone modes are 3rd, 5th, 7th, and 9th. The actual frequency of oscillation of an overtone crystal is not an exact multiple of the crystal fundamental. As an example, a 60 MHz 3rd overtone crystal would physically look like a 20 MHz crystal. The main difference being that certain electrical parameters are optimized in order to provide frequency of oscillation to occur at 60 Mhz when used in an overtone oscillator circuit.

Crystals will also exhibit unwanted or spurious modes when oscillating at the design frequency. These unwanted modes are influenced by the crystal surface finish, diameter and thickness dimensions, and mounting technique. These spurious modes are expressed in terms of equivalent series resistance referenced to the design mode of the crystal, or in terms of energy level in dB referenced to the carrier frequency.

Normally a crystal is designed for optimum energy and performance at the desired operating frequency with spurious energy levels being suppressed to some degree. If spurious modes are of concern to the designer, every effort should be made to consult with the crystal manufacturer before finalizing the specification.

III. Crystal Equivalent Circuit, Motional Parameters, and Quality Factor

The quartz crystal can be represented electrically by the circuit shown in figure 6. The motional inductance (L_m), motional capacitance (C_m), and series resistance (R) form a series resonant CIR order of 4 to 7 pF. All these motional parameters can be measured using a crystal impedance (CI) meter.
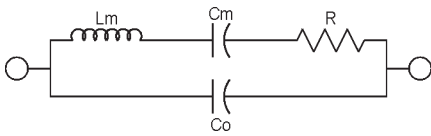
Figure 6

Normally the actual values for these motional parameters are a function of the design frequency. In applications requiring control of spurious responses or where the crystal needs to be "pulled" in frequency, the designer may need to specify the desired motional parameters. The series resonant frequency (Hz) of the crystal is represented by the formula:

$$Fs = \frac{1}{2\pi \sqrt{Lm\ Cm}}$$

Where Lm is in Henries and Cm in Farads.

The "Q" of a crystal is the quality factor of the motional parameters at resonance. The maximum stability of a crystal is directly related to the "Q" of the crystal. The higher the "Q" the smaller the bandwidth and the steeper the reactance curve. See figure 6. The "Q" can be expressed as:

$$Q = \frac{1}{2\pi\ Fs\ R\ Cm} = \frac{2\pi\ Fs\ Lm}{R}$$

IV. Series and Parallel Resonance

When a crystal is operating at series resonance (f_s), see figure 7, it appears resistive in the oscillator circuit. The impedance of the crystal is near zero at resonance. No load capacitance needs to be specified for crystals intended for use in a series resonant oscillator circuit. Most higher overtone (5th, 7th, and 9th) crystals will be specified as series resonant types.

When a crystal is operating at parallel or anti resonance (f_a), see Figure 7, it appears inductive in the oscillator circuit. The crystal's impedance is highest at this anti-resonance point. Under this condition the crystal is sensitive to changes in circuit reactance values. For crystals operating in a parallel resonant oscillator the load capacity of the crystal should always be specified in order to insure proper frequency control and operation.
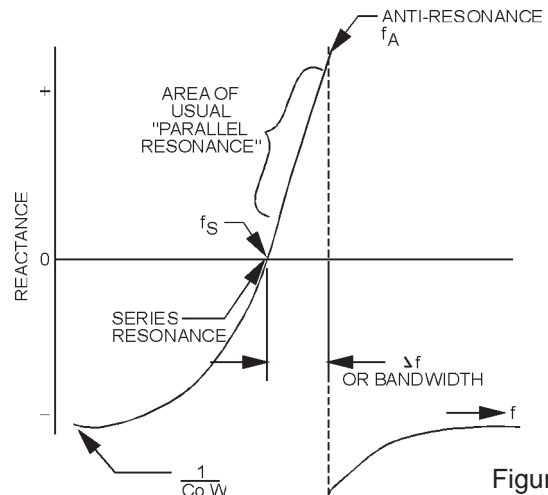
Figure 7

V. Crystal Loading

The loading of the crystal is critical in order to have a properly functioning oscillator. Figure 8 shows a typical Pierce oscillator comprised of an HCMOS inverter being used as an active linear device.
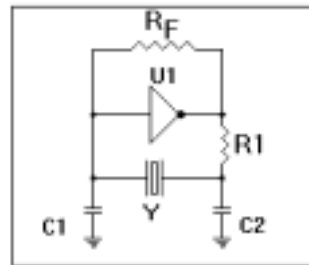
Figure 8

This circuit is commonly used with fundamental mode crystals. The inverter is biased into a linear mode by feedback resistor R_F. Depending on the frequency of operation, this feedback resistor will usually have a value in the 500K to 2 Meg ohm range. Resistor R_1 can be used to control the drive to the crystal and will typically have a value that is about equal to the reactance value of capacitor C_2. Values will range between 200 to 2700 ohms typically.

In some applications this resistor may not be needed. Careful selection of capacitors C_1 and C_2 will insure optimum startup and loading conditions for the crystal. The capacitor values are critical because the oscillator circuit relies on wideband noise in order to get the oscillator to start. Ideally the inverter stage will provide a 180° phase shift between its input and output. The crystal and the two capacitors provide additional 180° phase allowing for in-phase energy to be applied to the input of the inverter stage. This completes the feedback loop and oscillation can occur as long as the inverter can provide a voltage gain that is greater than 1. Because the crystal in this ex-

ample is capacitively loaded, it is considered to be a parallel resonant mode crystal. In other words, when the crystal was built and adjusted to its final frequency, it was calibrated into a capacitive load. A parallel resonant mode crystal needs to have a load capacitance (C_L) specified when ordering. The approximate crystal loading for a given circuit can be determined from the formula:

$$C_L = \frac{C_1 \; C_2}{C_1 + C_2} + C_S$$

C_S is the stray capacitance of the circuit and the input/output capacitance of the inverter.

Typically values for C_S is on the order of 4 to 8 pF. If the crystal (Y) in figure 7 is designed to operate at parallel resonance with an 18 pF load, then the C_L of the circuit should represent an 18 pF load to the crystal.

In this example, typically C_1 and C_2 could have values ranging from 27 to 32 pF. It can be seen from the C_L formula that there is more than one combination of C_1 and C_2 values that can equal 18 pF.

In most cases equal values of C_1 and C_2 can be used. In some applications an optimum value for C_1 will be approximately 75 to 90% of the value of C_2. Most crystal manufacturers will specify standard parallel resonant load capacitances of either 18 or 20 pF. These values have been found to provide for good stability when used in a circuit similar to that shown in figure 7. C_L values below 13 pF should be avoided if possible.

VI. Pullability or Trim Sensitivity and Tolerance Accuracy

As C_L values approach the shunt capacitance (C_0) value of the crystal, the trim sensitivity (pullability) increases making the crystal more sensitive to changes in the oscillator circuit.

While crystals calibrated with low C_L values can be provided, there is an increased potential for correlation problems to occur between the crystal manufacturer and the end user. The formula for trim sensitivity is:

$$\Delta f / pF = \frac{10^6 \; Cm}{2(C_0 + C_L)^2}$$

The crystal tolerance is a measurement of the degree of accuracy of the crystal at room temperature (+25°C). Crystals can be specified with a given value of roomset toler-

ance, such as ± 25 ppm at + 25 °C.

If the C_L gets very small, the $\Delta f / pF$ increases. Also, as the motional capacitance (C_m) increases the $\Delta f / pF$ increases. For a 10.000 MHz crystal with C_m of 0.020 pF, and a C_0 of 4.5 pF, a C_L of 10 pF would result in a trim sensitivity of 48 ppm/pF.

If the accuracy of the load capacitance (C_L) is ± 0.5 pF, then the accuracy of this tolerance measurement is ± 24 ppm. If the C_L is changed to 20 pF the trim sensitivity would be 16 ppm/pF.

With a load accuracy of ± 0.5 pF the measurement accuracy would be ± 8 ppm instead of ± 24 ppm with the 10 pF load. As can be seen, in cases where tight values of roomset tolerance (< 10 ppm) are required correlating to measurements taken with low values of C_L can become a problem.

VII. Stability Tolerance Vs. Frequency Tolerance

The stability tolerance is the maximum allowable deviation from the crystal frequency over a defined operating temperature range. The stability tolerance is usually stated in parts per million (ppm) and is referenced to the frequency of the crystal at room temperature (+25°C).

The frequency tolerance of the crystal is the maximum allowable deviation from nominal frequency at a specified temperature, usually +25°C. The stability tolerance of a crystal needs to be specified along with the operating temperature range. For instance, a crystal may be specified as having a stability tolerance of ± 50 ppm over an operating temperature of -45°C to + 85°C, and having a frequency tolerance of ± 50 ppm at +25°C.

In this example the crystal could theoretically exhibit a worst case frequency deviation from nominal of ± 100 ppm. Making the tolerance value smaller will result in a lower overall worst case frequency deviation over operating temperature.

Stability or frequency tolerance is sometimes expressed as a percentage of frequency deviation rather than as parts per million (ppm). The conversion is not difficult if you remember that .01% is the same as 100 ppm, .005% is 50 ppm, .001% is 10 ppm, etc.

VIII. Crystal Drive Level

The drive level of a crystal is a measurement of the power dissipation experienced by a crystal in a given circuit. The drive level is expressed in milliwatts (mW) or microwatts (µW). The maximum power dissipation is generally specified by the crystal manufacturer. The drive level of a crystal is a function of the reactance of the input and output capacitance of the inverter or active device and all other external components including the crystal.

The crystal manufacturer assumes that the oscillator circuit in which the crystal is to be used has enough drive capability to provide energy to start the crystal and sustain oscillation.

Most crystals that are used with an inverter circuit such as shown in Figure 8, or with any one of a number of microprocessor/controller chips, will have a drive specification in the range of 100 to 500 µW range.

If the oscillator is operated from a nominal supply voltage of 5 volts and is properly optimized, it is unlikely that any drive problems should be experienced. Drive level is more critical when using tuning fork crystals such as the M-tron MMCC-1, MMCC-2, and the SX 1555.

These crystals are usually rated at 1 µW maximum drive. Circuits using these types of crystals need to be designed in such a way so as not to overdrive the crystal. A crystal that is overdriven can be fractured or damaged by excessive power dissipation, or it may become erratic in frequency, often operating on an overtone rather than the fundamental design frequency.

IX. Crystal Equivalent Series Resistance (ESR)

The equivalent series resistance is the resistive (R) element of the quartz crystal equivalent circuit (See figure 6). This resistance represents the equivalent impedance of the crystal at series resonance.

ESR values are generally stated as maximum values. The ESR values vary with frequency, mode of operation, holder type, crystal plate size, electrode size and mounting structure. The standard instrument used to measure ESR is the crystal impedance (CI) meter.

It is important to note that the ESR value at a given frequency for an AT- strip crystal design is generally higher than that of the standard plano-plano (round blank) design. When making the transition from a through-hole HC-49/U type crystal to a smaller surface mount type utilizing an AT-strip crystal some consideration may need to be given to the difference in the ESR values.

This is especially true at low frequencies. For instance a M-tron 4.000 MHz MP-1 (HC-49/U type) crystal may have an ESR value of 75 ohms max., whereas the M-tron SX2050 surface mount crystal at the same frequency has an ESR of 150 ohms max. The difference being that the MP-1 uses a larger round crystal blank design and the SX2050 uses the smaller AT-strip crystal design.

ESR values become important when resistance values reach a point were the oscillator circuit cannot adequately drive the crystal. This may result in sluggish start-up or operation of the crystal at an unwanted mode.

X. Crystal Aging Characteristics

Aging is a natural phenomena that occurs with a crystal over time. Aging is a result of changes in the external or internal environment of the crystal. Most of the aging effects of a crystal occur within the first year of life of the crystal. The degree of hermeticity of the crystal package is a major factor in determining how well a crystal will age.

The normal level of hermeticity of a resistance weld HC-49/U crystal package is on the order of 1×10^{-8} atmospheres in cc/Sec minimum. If this minimum level is not achieved in the manufacturing process, the crystal will experience the ingress of ambient atmosphere and humidity.

These external elements enter the crystal package and contaminate the crystal blank surface. This contamination causes shifts in the crystal's nominal frequency. Other effects are resistance changes, and possible spurious mode generation.

Another external condition that can cause excessive aging to occur is exposure of the crystal to high temperatures, beyond the recommended storage temperature, for extended periods of time. In some instances the high temperatures seen in various solder processes can cause aging to occur.

If the integrity of the hermetic crystal package is degraded, moisture can enter the crystal package when undergoing washing and cleaning processes. Loss of hermeticity can occur because of fractured glass-to-metal seal around the leads of the crystal, or damage to the weld flange of the crystal. Proper handling and storage of the crystal units is important in order to prevent damage to the crystal package and thereby causing loss of hermeticity.

Internal effects of the crystal will have an affect on aging. Over time, the exposure of the crystal unit to temperature extremes, shock and vibration will cause outgassing and particulate contamination to occur inside the crystal.

The result of this condition is that some of the contamination finds its way to the surface of the crystal blank. To minimize the aging effect in crystals several things can be done. The use of a cold weld crystal package such as the HC-43/U type will typically improve long term aging characteristics. Crystals can be preaged by submitting them to a burn in at some elevated temperature for a defined period of time.

Crystal units can be assembled in a clean room environment where particulate material content and humidity levels are controlled. Higher levels of "clean" vacuum can be used when sealing the crystal units. The use of low outgassing materials within the crystal package will also help aging characteristics.

The HC-49/U resistance weld package will typically exhibit better aging characteristics than the older HC-18/U solder seal type of crystal package. The solder seal package inherently contains contaminants from the soldering process and can lose hermeticity when going through certain reflow solder processes. The HC-18/U for all practical purposes has been replaced by the resistance weld HC-49/U package.