Piezoelectric Effect

Quartz, composed of Silicon and Oxygen (Silicon Dioxide), exhibits piezoelectric properties. It generates an electrical potential when a pressure is applied on the surfaces of the quartz crystal. Inversely, when an electrical potential is applied to the surfaces of a quartz crystal, mechanical deformation or vibration is generated. These vibrations occur at a frequency determined by: a) the physical dimension of the piece of quartz crystal; b) the cut of the piece in relation to the crystalline axes of the quartz; c) the operating temperature; d) the oscillator circuit.

Equivalent Circuit Parameters

The well-known equivalent circuit used to represent a quartz resonator in the vicinity of the main mode of vibration is shown in the following Figure 1.

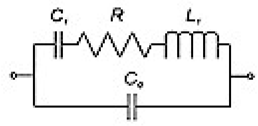

Fig.1 Equivalent Circuit

It is valid as long as the main mode is isolated from other modes of vibration. Co represents the static capacitance of the electrodes and package, while L_1, C_1, and R represent the electrical equivalent of the mechanically resonant main mode. The latter are known as motional elements and form the motional arm of the equivalent circuit. Away from the main mode there are many other resonances that can be similarly represented by the parallel addition of other motional arms. When writing a specification for a quartz crystal, the individual parameters of the equivalent circuit should be examined. For all designs, there are limits for each type of crystal design.

C_0: The shunt capacitance of a crystal is due in part to the thickness of the wafer. This is the measure capacitance while not vibrating. Shunt capacitance ranges from 1 to 7 pF. It is not typical to exceed 7 pF due to compatibility with the oscillator circuit.

C_1: The motional capacitance of a crystal is determined by the stiffness of the quartz (constant), the area of metalization (electrode size) on the face of the crystal and the thickness and the shape of the wafer. At lower frequencies, the wafer must be shaped (contoured or beveled) to improve the performance of the device. This will lower the C_1 of the device. The C_1 for fundamental mode crystals can range from approximately 5 fF to 30 fF. As a general rule, if a fundamental design is used on an overtone, the C_1 will divide by the square of the overtone (i.e., 3rd overtone will be 1/9 of the fundamental).

L_1: The motional inductance of the crystal is determined by the mechanical mass of quartz in motion. The lower frequencies (thicker and larger quartz wafers) tend to run at a few Henries, while higher frequencies (thinner and smaller quartz wafers) tend to run at a few milli-Henries. The L_1 and C_1 are related by Thomson's formula: $L_1 = 1/(4\pi^2 f^2 C_1)$. It is preferable to have the customer specify C_1 (if necessary). Then the L_1 will follow the above formula.

Frequency-Temperature Characteristics

The frequency-temperature characteristics are determined by the design of a quartz crystal resonator, the cut angle and the mounting structure. They can be grouped into two types according to the shape of the corresponding curves. One is ternary or third-order, and the other a quadratic or second-order curve. Fig.2 shows an AT-cut characteristic representing a third-order parabola curve. Their inflection point, which depends on the resonator design, is situated between +25°C and +35°C. AT-cut crystal resonators are the most extensively used and are characterized in that they produce small frequency changes in response to temperature changes in the ambient temperature.

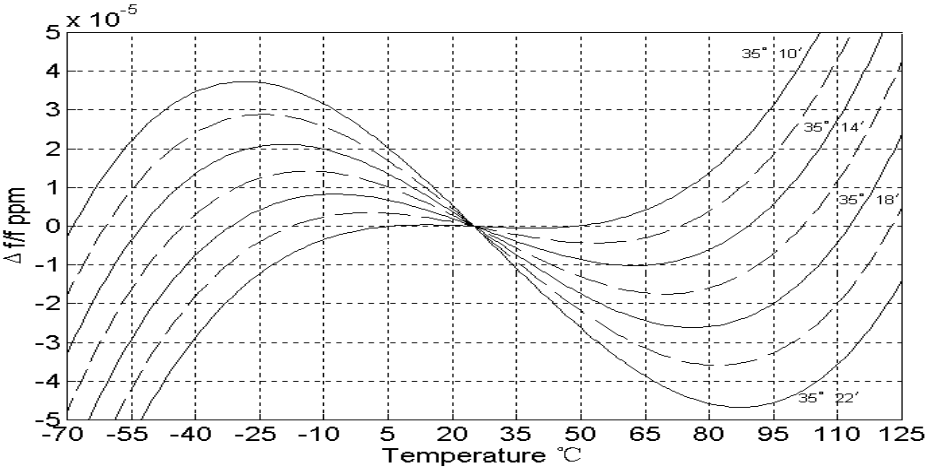

Fig.2 AT-cut frequency-temperature characteristics

Frequency Tolerance or Calibration Accuracy

The calibration tolerance is the maximum allowable deviation from nominal frequency at a specified temperature (typically 25 degree C). It is normally specified in parts per million (ppm) or percentage of nominal frequency. The overall frequency tolerance is the maximum allowable deviation from nominal frequency due to changes in temperature, time and all other environmental conditions.

Frequency Stability

Frequency stability is the maximum allowable deviation from the nominal frequency over a specified temperature range, and is specified in parts per million (ppm) or percentage of nominal frequency. Deviation is usually referenced to the measured frequency at 25 degree C. This parameter depends on the following factors: type of quartz cut, angle of the quartz cut, mode of operation, and mechanical dimensions of the quartz blank.

Series Resonance vs. Parallel Load Resonance

A quartz crystal resonator can be used in a circuit to operate in either of the two modes, series or parallel. Series resonant crystal and parallel load resonant crystal are physically the same crystal, but are calibrated to slightly different frequencies. When a crystal is placed into an oscillator circuit, they oscillate together at a tuned frequency. This frequency is dependent upon the crystal design and the amount of load capacitance, if any, that the oscillator circuit presents to the crystal. Load capacitance, specified in pico Farads (pF), is comprised of a combination of the circuit's discrete load capacitance, stray board capacitance, and capacitance from semiconductor miller effects. When an oscillator circuit presents some amount of load capacitance to a crystal, the crystal is operated at the condition of "Parallel Load Resonance", and a value of load capacitance must be specified. Typical values of load capacitance are 18pF, 20pF, 22pF, 30pF and 32pF. The frequency decreases as the value of the load capacitance increases, correlated by the following equation:

$$F_L = F_S\,[C_1/2(C_0 + C_L) + 1]$$

Where:

F_L = Parallel Load Resonant Frequency (MHz)
F_S = Series Resonant Frequency (MHz)
C_L = Crystal Load Capacitance (pF)
C_0 = Crystal Shunt Capacitance (pF)
C_1 = Crystal Motional Capacitance (pF)

If the oscillator circuit does not exhibit any capacitive loading, the crystal is operated at the condition of "Series Resonance", and no value of load capacitance need to be specified. Crystals operating at series resonance appear resistive in the circuits, and such circuits depend entirely on the crystal unit to provide the phase shift necessary to start and maintain oscillation at the specified frequency.

Equivalent Series Resistance (ESR)

ESR is the resistive element, measured in Ohms, of a quartz crystal resonator. For crystals designed to operate as series resonance, ESR is the equivalent ohmic resistance of the unit when the motional inductance (L_1) and motional capacitance (C_1) are of equal ohmic value but are exactly opposite in phase. The net result is that they cancel one another and only a resistance (R) remains in the series leg of the above equivalent circuit (Fig.1). The ESR measurement is made only at the series resonant frequency (F_S), not at some predetermined parallel resonant frequency (F_L). Crystal resistance measured at some parallel resonant frequency is often called the "effective" resistance. Generally, the lower the resistance value of a crystal, the more active it is and less drive is required to activate it. If the ESR is too high, then the crystal may not oscillate. However, lower values than those standard specifications will result in a unit cost increase due to the additional processes required to achieve those ESR values.

Drive Level

The drive level, expressed in microwatts or milliwatts, is the power dissipation level at which the crystal resonator is designed to operate. Maximum power is the most power a crystal resonator can dissipate while still maintaining operation with all electrical parameters guaranteed. Operating the crystal at drive levels that are too high or too low can result in improper performance. For example, if the drive level is too low, the crystal may fail to oscillate or have degraded phase noise performance. On the other hand, if the crystal is driven at too high a level, the results could include frequency shifts (permanent or temporary), crystal activity dips (related to frequency temperature discontinuities), excessive aging or, in extreme case, physical failure of the crystal resonator. In addition, maximum specified ESR of the crystal is affected by and is measured at predetermined drive level. Therefore, it is important to operate the crystal resonator at a suitable drive level.

Fundamental Mode and Overtone Mode

High frequency (MHz range) AT-cut crystals vibrate in the thickness-shear vibration, which can be excited in fundamental or odd overtone modes. The mode of operation of a quartz crystal will determine the frequency of oscillation. For example, a crystal may operate at its fundamental frequency of 10 MHz, or at odd harmonics of approximately 30 MHz (3rd overtone), 50 MHz (5th overtone), and 70MHz (7th overtone). The equivalent circuit of an overtone mode would simply be an additional parallel (R, C_1 and L_1) branches (no additional C0 branch) equivalent to the fundamental circuit as shown in Fig.1. Overtone crystals are specially processed for plane parallelism and surface finish to enhance its performance at the desired overtone.

Pullability

The pullability of a crystal refers to a crystal operating in the parallel mode and is a measure of the frequency change as a function of load capacitance. The amount of pullability exhibited by a given crystal resonator at a given value of load capacitance is a function of the shunt capacitance C_0 and the motional capacitance C_1 of the crystal unit, as well as the value of load capacitance. An approximation of the pulling limits for standard crystals can be obtained from the following formula:

$$F_L - F_S = F_S C_1 / 2(C_0 + C_L)$$

Pullability is important to the circuit designer who needs to obtain several operating frequencies from a crystal unit by changing in values of load capacitance. For example, in certain applications (i.e., VCXO) where variations in the crystals parallel resonant frequency are mandatory, pullability is specified.

Spurious Response or Unwanted Modes

Vibrations at frequencies that are not fundamental or overtone modes of a crystal resonator are referred to as spurious or unwanted modes. All resonating crystal vibrators produce a main mode for each overtone, which is a thickness shear vibration for AT-cut, and also unwanted responses, which are inharmonic thickness shear modes above the resonance frequency. These unwanted responses are influenced by many factors including the dimension of the quartz wafer, the surface finish, the size and thickness of the electrode and the mounting technique. In a poorly designed crystal resonator, the ESR of the crystal at the spurious mode can be less than that at the main mode and result in spurious oscillation or frequency jumps in oscillator circuit. Other undesired effects are frequency and resistance dips over temperature caused by unwanted modes. Spurious mode is generally specified in terms of minimum resistance ratio between the spurious mode and the main mode.

It is sometimes necessary to specify the suppression of the overtone responses for some oscillator designs. Since all the overtone responses can be excited into vibration, a mode hop from the fundamental to the 3rd overtone can occur. Proper oscillator design may also be needed or desired to reduce circuit modification costs. These modifications can sometimes affect other parameters so it is wise to contact the factory to discuss design options.

Aging or Long-Term Stability

Long-term stability or aging of a quartz crystal is a measure of the frequency stability over an extended time period and is usually expressed in terms of parts per million (ppm) per day or year. It applies to the cumulative process which contributes to the deterioration of the crystal unit and which results in a permanent change in operating frequency of the crystal unit. Aging normally follows an exponential progression over time, so that most aging takes place in the first few months after manufacture. This process can be accelerated by operating the crystal at an elevated temperature for an extended, by temperature cycling or by high temperature bake or burn-in.

There are many interrelated factors involved in aging. Some of the most common are: internal contamination, crystal surface changes, wire fatigue, small irreversible changes in the crystal lattice, outgassing of the materials, various thermal effects, mounting stresses, and over-driving the crystal. Typical aging figures for metal enclosure crystal units operating in the frequency range of 10 to 20 MHz are 1.0 – 5.0 ppm / 1st year; while the values for glass enclosure crystals are 0.1 – 1.0 ppm / 1st year.

Storage Temperature

The storage temperature range applies to minimum and maximum temperatures that the devices can be stored or exposed to when in a non-oscillation state. After exposing or storing the device at the minimum or maximum temperatures for a length of time, all of the operating specifications are guaranteed over the specified operating temperature range.