Principles of Quartz Crystal Operation

QUARTZ PRINCIPLES OF OPERATION

Quartz crystal units serve as the controlling element of oscillator circuits by converting mechanical vibrations to electrical current at a specific frequency. This is accomplished by means of the “Piezoelectric” effect. Piezoelectricity is electricity created by pressure. In a piezoelectric material, the application of mechanical pressure along one axis will result in the creation of an electrical charge along an axis at right angles to the first. In some materials, the obverse piezoelectric effect is found, which means that the imposition of an electric field on the ends of an axis will result in a mechanical deflection along an axis at right angles to the first. Quartz is uniquely suited, in terms of mechanical, electrical, and chemical properties, for the manufacture of frequency control devices. Quartz crystal units that oscillate within certain frequency and temperature ranges have been developed over the years.

The most practical raw material for quartz crystals is crystalline silicondioxide, SiO_2. This results from its mechanical and chemical stability, together with a favorable piezoelectric constant. The small frictional losses in the material guarantee the manufacture of electromechanical oscillators of very high quality factors.

In nature, silicondioxide is found in different forms, one of which is quartz. Even though 14% of the earth’s surface consists of silicondioxide, quartz of suitable size and necessary purity is seldom found. As a result, cultured quartz has been developed. Cultured quartz is achieved from hot saturated solutions of silicondioxide, in large steel autoclaves at a temperature of some 400°C and a pressure of 1,000 Kgs/cm^2. The axial growth of the crystal is controlled by previously cut seeds planted in the autoclaves. The growth rate can be as much as 2.5 mm per day. In order to achieve a pure crystal, a controlled slow rate of growth is preferred. The yield of quartz crystals from cultured quartz is higher than when grown quartz is used.

Temperature coefficient has to do with the frequency stability of a quartz blank with respect to changes in temperature, which is a function of quartz, the mode of vibration, and the type of cut. The frequency- temperature curve generalized for high frequency AT crystals, known as the frequency deviation (in PPM) at a specified temperature range (in °C), the family of curves can be used to define maximum allowable deviation (in minutes) around the center for cutting the blank.

Of the various elements, the “AT” cut has become the most popular, because it is available at relatively high frequencies, exhibits excellent frequency vs temperature stability, and is widely available at reasonable cost.

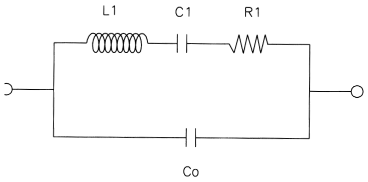
Fundamental vs. Overtone is of concern primarily when specifying the “AT” cut crystal unit. These units increase in frequency as the thickness of the resonator plate is diminished. At some point, typically around 30 MHz, the plate becomes too thin for efficient processing. As the “AT” will resonate at odd integer multiples of the fundamental frequency, it is necessary to specify the desired order of overtone when ordering higher frequency crystals.

Drive level is the amount of power dissipated by the crystal. Drive level is usually specified in terms of micro or milliwatts, with a typical value being 100 microwatts.

“Series” resonant crystals are intended for use in circuits containing no reactive components in the oscillator feedback loop. ***“Parallel” resonant crystals*** are intended for use in circuits containing reactive components (usually capacitors) in the oscillator feedback loop. Such circuits depend on the combination of the reactive components and the crystal to accomplish the phase shift necessary to start and maintain oscillation at the specified frequency.

Pullability refers to the change in frequency of a crystal unit, either from the natural resonant frequency (F_R) to a load resonant frequency (F_L), or from one load resonant frequency to another. The amount of pullability exhibited by a given crystal unit 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.

The ***equivalent circuit*** of a quartz crystal is useful in explaining how a crystal will perform.



C_0 is the shunt or static capacitance of a crystal. This parameter equals the sum of the capacitance measured from pin to pin including the electrode and mounting structure.

L_1, C_1, and R_1 are the motional arm of the crystal.

L_1, motional inductance, is determined by the mechanical mass of quartz in motion. Thompson’s formula relates the L_1 and the C_1 specifications.

$$L_1 = \frac{1}{4\pi^2 f^2 C_1}$$

C_1 is the motional capacitance of the crystal. This parameter is determined by the stiffness of the quartz (constant), the area of the electrode, and the thickness and shape of the quartz wafer.

R_1 stands for the equivalent series resistance (ESR) of a crystal. It is a function of the mechanical losses during vibration. Low resistance is a sign that little mechanical loss is occurring. The lower the resistance, the more easily the crystal will oscillate.

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Three main components of crystal specifications are:

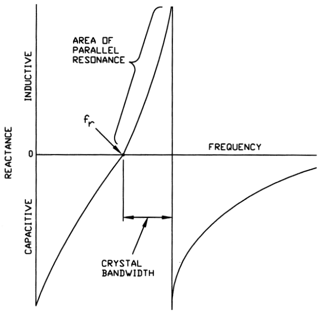
- Calibration at room temperature
- Stability over the temperature range
- Aging

Calibration at room temperature is a measurement of the accuracy of the frequency at +25°C. Crystal frequencies are adjusted within the stated tolerance by changing the mass of the electrode. Lower frequencies are less sensitive to mass change and are therefore easier to hold tighter tolerances. Tolerance and stability are measured in parts per million (ppm).

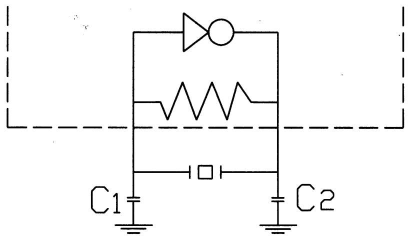
The angle at which the quartz bar is cut determines the ***stability*** over the temperature range. A very popular cut is the "AT" cut. The accuracy of the cut determines how tight the shifts in ppm will be over a temperature range.

Aging is defined as the change in frequency over time. Two factors affect this specification: contamination and stress. See the section on aging.

Load capacity is the dynamic capacity of the total circuit measured or computed across the crystal terminals. In a parallel circuit the load capacity should be selected to operate the crystal at a stable point on the fr-fa reactance curve (as close to fr as possible).



Below is an example of an oscillator circuit in which the crystal is expected to run in its parallel mode. If a series crystal is put into this circuit, the frequency would be high by approximately 0.02%.



Load capacitance (C_L), which is specified in picofarads (pF), can be calculated by the following formula:

$$C_L = \frac{C_1 * C_2}{C_1 + C_2} + \text{Cstray}$$

Cstray includes pin to pin, input and output capacitance of the oscillator stage at the C_1 and C_2 pins plus any additional parasitics. It is usually assumed Cstray equals 5 pF.
If C_1 and C_2 each equal 22 pF, then C_L = 16 pF.

If the oscillator stage is configured with a phase shift presented to the crystal exactly equal to 0° or multiples of 360°, then the crystal will operate at series resonance (fr). The crystal's load capacity must be specified "Series Resonance."

The Quality Factor (Q) Value of a crystal unit is a measure of the units relative quality, or efficiency of oscillation. The maximum attainable stability of a crystal unit is dependent on the "Q" value. The separation between the series and parallel frequencies is called bandwidth. The smaller the bandwidth, the higher the "Q" value, and the steeper the slope of the reactance. Changes in the reactance of external circuit components have less effect (less "pullability") on a high "Q" crystal; therefore such a part is more stable.

The U.S. military specifications (MIL-C-3098) for crystals define the ***equivalent resistance*** as follows:

For crystal units designed to operate at series resonance, equivalent resistance is the equivalent ohmic resistance of the unit when operating in the specified crystal impedance meter adjusted for the rated drive level and tuned to the specified crystal unit frequency.

For crystal units designed to operate at parallel or antiresonance, equivalent resistance is the equivalent ohmic resistance of the unit and a series load capacitor of the specified load value, when operating in the specified crystal impedance meter adjusted for rated drive level and tuned to the specified crystal unit frequency.

Operating ***drive level*** is the power dissipated internally in the crystal blank. It is very important to carefully determine and select a drive level that is consistent with reliable start up and the desired performance of the crystal once oscillating. If the drive level is too low (generally less than 100 microwatts), starting of oscillation may not occur. However, drive level that is too high (generally greater than 1 milliwatt) will cause frequency shifts, poor long–term frequency aging, and frequency perturbations over the operating temperature.

Aging is a general term used to describe the gradual

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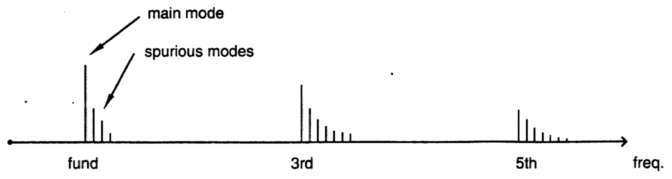
- f_s = Series Resonant Frequency = $\frac{1}{2\pi\sqrt{L_1C_1}}$
- f_a = Antiresonant Frequency = $\frac{1}{2\pi}\sqrt{\frac{1}{L_1C_1}+\frac{1}{L_1C_0}}$
- ΔF = Change in Frequency = $\frac{f_sC_1}{2(C_0+C_L)}$
- C_1 = Motional capacitance = $\frac{2(C_0+C_L)\,\Delta F}{f_s}$
- L_1 = Motional Inductance = $\frac{1}{4\pi^2 f_s^2 C_1}$
- R_1 = Series Resonant Resistance
- r = Capacitance Ratio = $\frac{C_0}{C_1}$
- Q = Quality Factor = $\frac{1}{2\pi f_s R_1 C_1}$
- R_a = Antiresonant Resistance
- C_0 = Crystal Shunt Capacitance
- C_L = Load Capacitance

deterioration of the operating characteristics of a crystal unit over time. Many factors contribute to this deterioration, such as internal contamination, excessive drive level, wire fatigue, frictional wear, and surface erosion of the crystal blank. Cleanliness of the manufacturing process and of the quartz blank can greatly reduce aging by contamination. The most rapid aging occurs within the first year. If aging rates of a crystal must be low, the crystal can be pre-aged by temperature-cycling or by high-temperature burn-in for an extended period of time.

All quartz crystals have multiple vibrational modes. ***Spurious modes*** refer to those that are unwanted and can be a problem if the response is as strong as the main mode. When the oscillator runs on the spur instead of the main mode, the frequency output is changed. Spurious modes should be specified as either a resistance ratio to the main mode or dB suppression. A resistance ratio of 1.5 or 2.0 to 1 is sufficient to avoid mode hopping. A -3dB to -6dB is an approximate equivalent for a specification in terms of dB.



Frequency Spectrum