Characteristics of Crystal

Piezoelectric effect of Quartz Crystal

The quartz crystal has a character when the pressure is applied to the direction of the crystal axis, the electric change generates on the quartz crystal plate, and on the contrary, when the electricity is applied to the quartz crystal plate, the distortion occurs inside the crystal plate. So, that’s why we called it’s the piezoelectric effect of quartz crystal.

Equivalent Circuit of Crystal

The equivalent circuit of a quartz crystal is shown to explain the basic elements governing the crystal characteristics and performance. It consists of a motional capacitance C_1, inductance L_1, series resistance R_1, and a shunted capacitance C_0. The first three parameters are known as the "motional parameters" of the quartz crystal element. See Fig. 1

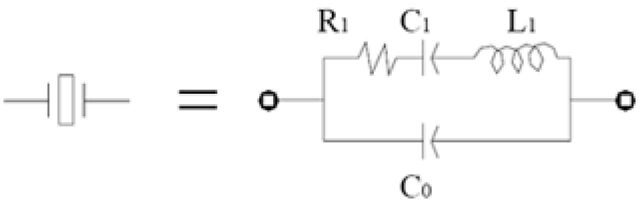


Figure 1

Series Resonance

When a crystal is operating at series resonance (Fs), it looks resistive in the circuit. Thus, impedance at Fs is near zero. In a well design series resonant circuit, correlation is not a problem and load capacitance does not have to be specified. See Fig. 2

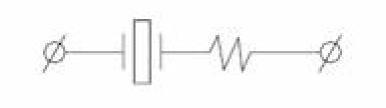


Figure 2

Parallel Resonance

When a crystal is operating at parallel resonance (Fs<Fl<Fa), it looks inductive in the circuit. Thus, function of a load capacitance is very important in selecting the stable point of oscillation. In parallel circuit design, load capacitance CL shall be specified. See Fig. 3

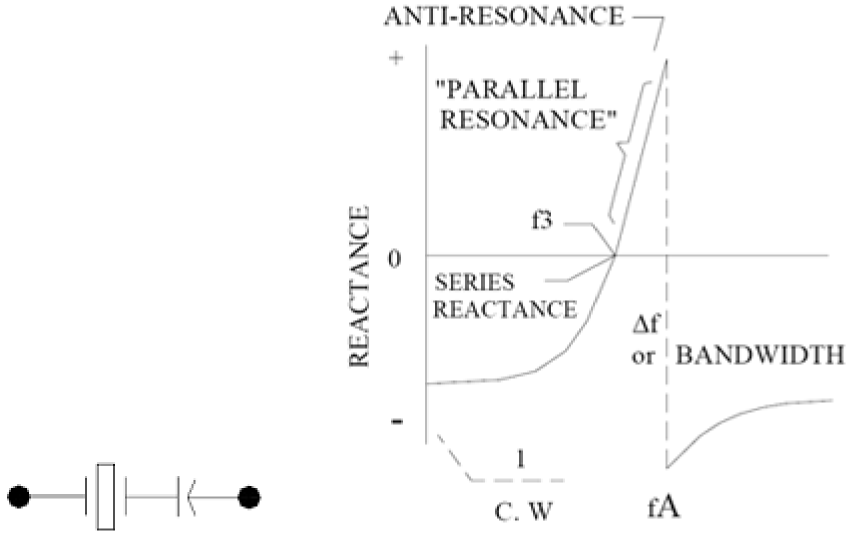


Figure 3

Difference between AT Cut AND BT Cut Crystals

AT cut crystals and BT cut crystals possess different angle cut (35 degrees on AT fundamental vs. 49 degrees on BT cut). Both types have the same vibration mode (thick-ness-shear). However, the BT cut crystal on the 50MHz fundamental is slightly thicker (2mils) compared to its AT cut (1.3mils). AT cut and BT cut have different temperature vs. frequency curves. (See Fig 4, 5 & 6)

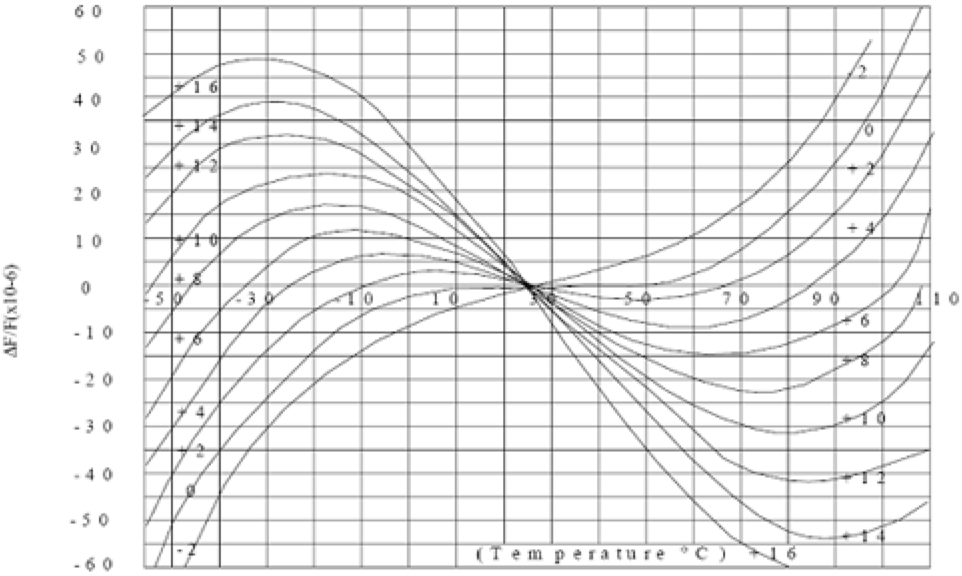


Figure 4. Frequency Temperature curves for AT Cut

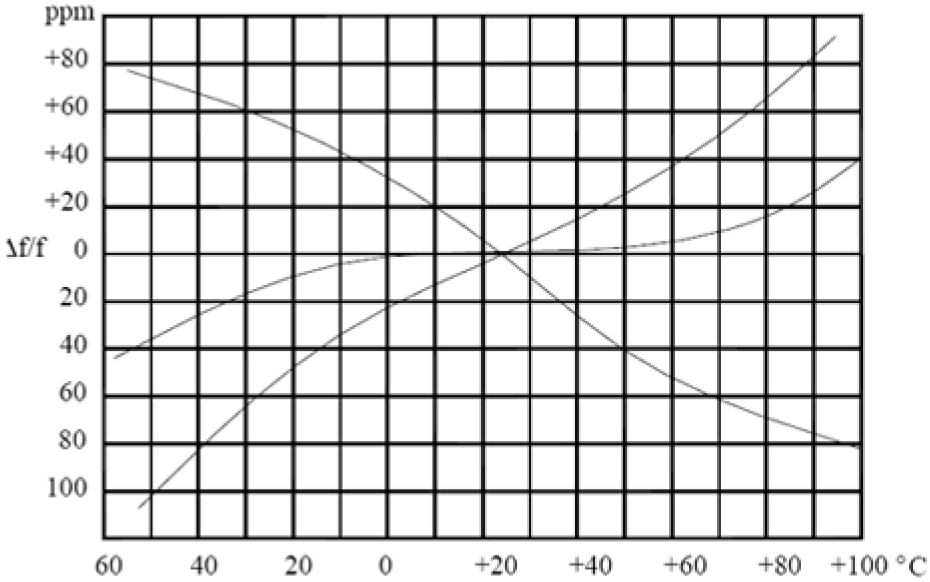


Figure 5. Typical Temperature characteristic for AT Cut Crystal

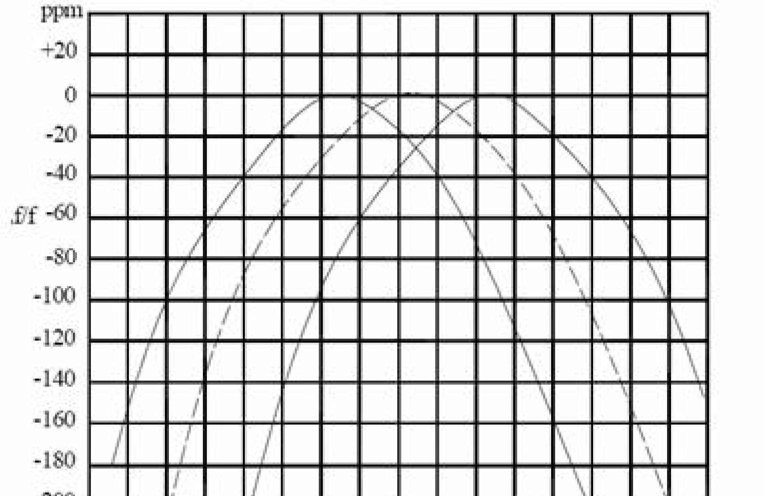


Figure 6. Typical Temperature characteristic for BT Cut Crystal

Thickness of AT Cut Crystal vs. BT Cut Crystal

$$\text{AT Fundamental} \quad F=\frac{1670}{t}$$

$$\text{AT Overtone} \quad F=\frac{1670\times n}{t} \quad \left\{\begin{array}{l}\text{F in KHz}\\ \text{t in mm}\\ \text{n =overtone mode}\end{array}\right.$$

$$\text{BT Fundamental} \quad F=\frac{2560}{t}$$

Crystal Unit Definitions

Crystal Unit

A case housing a thin piece of quartz crystal (silicon dioxide) or crystal strip with vacuum-evaporated metal electrode and terminals for connections. It is widely used as passive electronic component for mobile phones, wireless devices, telecommunication devices, personal computers and other digital equipments.

Frequency

The number of cycles of output waveform occurring per second. The unit of frequency is cycles per second, or Hertz, abbreviated Hz.

Fundamental Mode

The main mode of the crystal. It is also called first overtone.

Overtone Mode

Odd numbers assigned for frequencies in terms of specified oscillation mode. Standard third overtone mode, followed by fifth, seventh, ninth, etc. The frequencies are not exactly three, five, seven, or nine times the fundamental frequency.

Frequency Tolerance

This refers to the allowable deviation from the nominal frequency in parts per millions (ppm), at room temperature, usually +25º C.

Frequency Stability

This refers to the maximum allowable frequency deviation compared to the measured frequency at 25º C over specified temperature range, e g, -10ºC ~ + 70ºC.

Equivalent Series Resistance

The value of impedance the crystal exhibits in the operating resonant circuit.

Shunt Capacitance

Shunt capacitance (C0) is the capacitance between the crystal terminals. It varies with package, usually it is smaller in SMD (4pF typical) and is 6pF in leaded crystals.

Load Capacitance

This refers to external capacitance to the crystal, and the amount of capacitance measured or computed across the crystal terminal on the PCB. Load capacitance need to be specified when the crystal is used in a parallel mode. If the application requires a “series” resonant frequency crystal, load capacitance is not a factor and do not need to be specified. Load capacitance is calculated as follows:

$$C_L=\frac{(C_1\times C_2)}{(C_1+C_2)}+Cstray$$

Insulation Resistance

Resistance between crystal's leads, or between lead and case (metal case). It is tested with a DC voltage at 1 OOV ± 15V and insulation resistance is 500 MΩ(min.).

Drive Level

The amount of power dissipation experienced by the crystal in the oscillation circuit. The power is a function of the applied current and usually expressed in Milliwatts or Microwatts. Excessive drive level will result in possible long-term frequency drift and unstable operation increased aging rates or crystal fracture. The drive level may be calculated by the following equation:
Power = $(I\ rms^2 * RL)$
Where I is the RMS current through the crystal unit and R is the maximum resistance value of the specific crystal unit in question. This equation is simply “ Ohms Law” for power. Measurement of the actual drive level in an operating oscillation circuit maybe accomplished by temporarily inserting a resistor in series with the crystal unit. The resistor must be of the ohmic value as the unit. The voltage drop across the resistor may then be read and the current and power dissipation calculated. The resistor must then be removed. As an alternative way of measuring the drive level, a current probe may be used at the output lead of the crystal unit, space permits. The method is described as below

$$RL = R1\left(1 + \frac{C0}{CL}\right)^2$$

Fig7.

Where
RL = loaded resonance resistance
R1 = resonance resistance of crystal unit
Iq = current flowing to crystal unit
C0 = shunt capacitance
CL = load capacitance

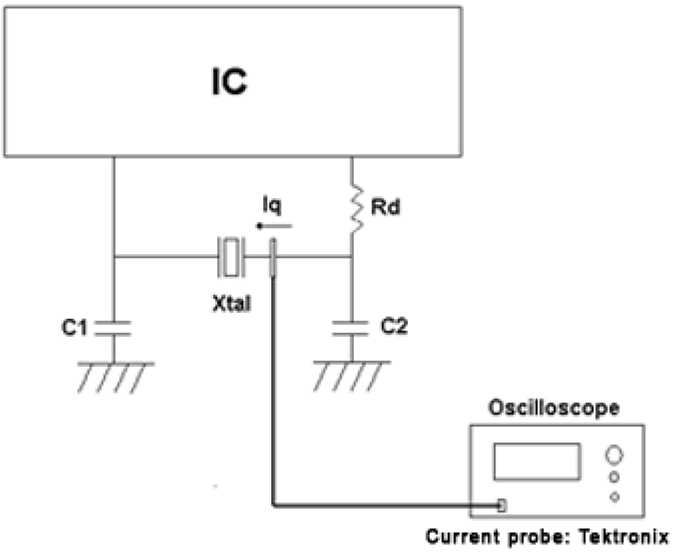


Figure 7.Drive level measurement

Aging

This refers to the cumulative change in frequency over a certain period of time. This rate of change of frequency is fastest during the first 45 days of operation. Many Interrelated factors are involved in aging, some of the most common factors are:
(1) Excess drive level,
(2) Internal contamination,
(3) Crystal surface change,
(4) Wire fatigue
(5) Various thermal effects
(6) Frictional wear, etc…

All these problems can be minimized by proper circuit design incorporation low operating temperature, min. drive levels and static pre-aging.

Spurious
It is also possible for a crystal to vibrate at a frequency that is not related to its fundamental or overtone frequency. Such unwanted frequencies are referred to as spurious. Spurious are usually above the operating mode, specified in dB max. or number of times of ESR. Frequency range must be specified.

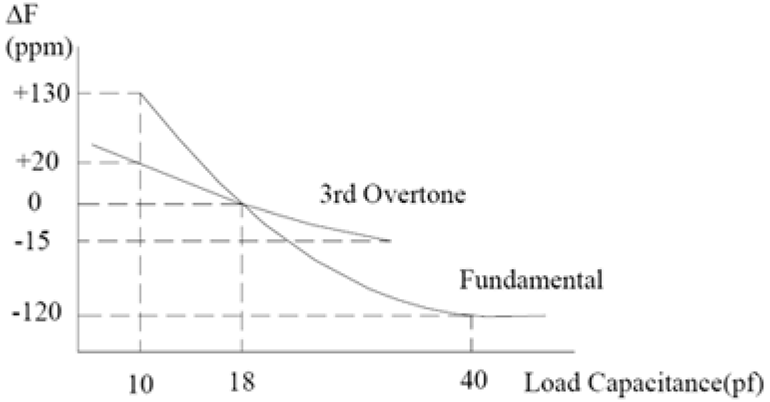
Operating Temperature Range
Temperature range within which crystal units operate under specified conditions.

Mode of Vibration
It is a piezoelectric effect of quartz crystal. The mode of vibration of quartz crystal varies with crystal cuts such as Thickness-shear for AT cut and BT cut, or Length-width flexure for tuning fork crystals (+2º) X cut. The most popular cut is the AT-cut, which offers a symmetrical frequency shift over a wide temperature change.

Change of Load Capacitance and 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. Pullability is important to the circuit designer who wishes to achieve several operating frequencies with a single crystal by means of changing in values of load capacitance.
When a crystal is operating at parallel resonance (Fs<Fl<Fa), it looks inductive in the circuit. As the reactance changes, the frequency changes correspondingly, thus changing the pullability of the crystal. The difference in frequency between the Fs and Fa depends on the C0/Cl ratio of the crystal unit. Equation of the pulling range between two load capacitances is given below:

$$D_{L1/L2} = \frac{f_{L1} - f_{L2}}{f} = \frac{C1\,(C_{L2} - C_{L1})}{2\,(C0 + C_{L1})\,(C0 + C_{L2})}$$

The same crystal with frequency at third-overtone mode will have much less pulling because its motional capacitance Cl' is approximately 1/9 of Cl at fundamental.



Frequency pullability of a fundamental vs. Its 3rd overtone crystal. The oscillating mass of the quartz crystal corresponds to the motional inductance Ll while the elasticity of the oscillating body is represented by the motional capacitance Cl.

Crystal Unit Application Notes

This application note describes the selection of a crystal used with any type of micro-controller that accepts a parallel mode, AT or BT cut crystal, fundamental or third-overtone mode.

Circuit Description
Most chips include an inverter design with a positive feedback resistor (typical 1 M ohm) with an optional series resistor with value varied from 100 to 1k ohm (See Fig 8).

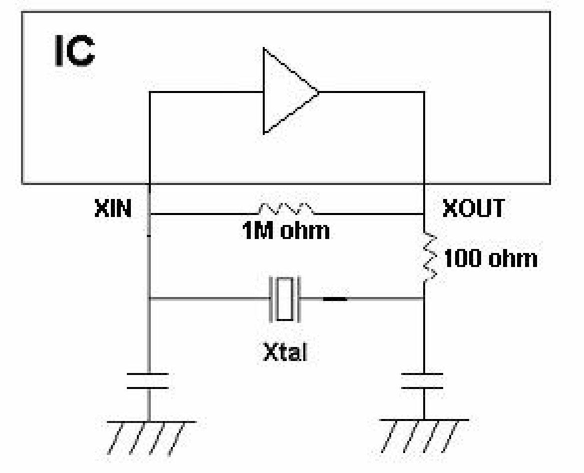


Figure8.Oscillation Circuit

It has an input port, normally called (XIN) and an output port (XOUT) for crystal connections between those two ports. Most chips are designed with an option either driven by an external crystal oscillator fed to the crystal input port, or with an external crystal.

Depending on frequency, crystals can be selected as fundamental or an overtone mode. Normally, frequency above 35 MHz requires the third overtone mode for price advantage and delivery. In parallel mode, where the crystal reactance is inductive, two external capacitors Cl and C2 are required for a necessary phase shift in oscillation. Cl and C2 are needed whether the crystal is in fundamental mode or overtone mode. Values of Cl and C2 are specified by the chip manufacturer and vary from 6pF to 47pF. Cl and C2 may not be balanced, e g, equal in value, but sometimes are offset in a particular ratio (Cl/C2) for best performance, depending on crystal and amplifier characteristics and board layout. (See Fig 9) shows a typical configuration for a fundamental mode operation.

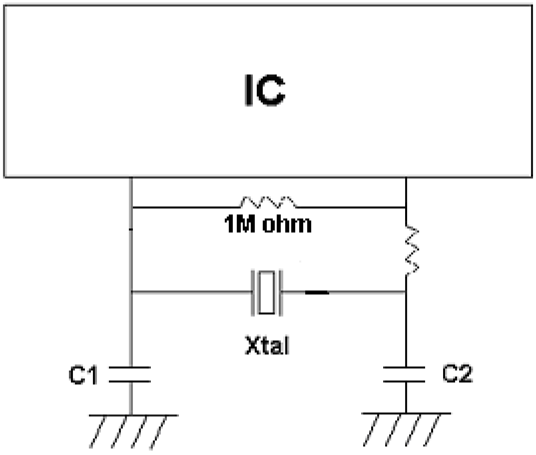


Figure 9. Fundamental Mode Oscillation Circuit

In an overtone mode, an additional inductor Ll and capacitance Cc is required to select the third overtone mode while suppressing or rejecting the fundamental mode. Choose Ll and Cc component values in the third overtone crystal circuit to satisfy the following conditions:

1. The LlCc components from a series resonant circuit at a frequency below the fundamental frequency, which makes the circuit look inductive at fundamental frequency. This condition does not favor to oscillation at fundamental mode.
2. The LlCc and C2 components form a parallel resonant circuit at a frequency about half-way between the fundamental and third overtone frequency. This condition makes the circuit capacitive at the third-overtone frequency, which favors the oscillation at the desired overtone mode. (See Fig 10).

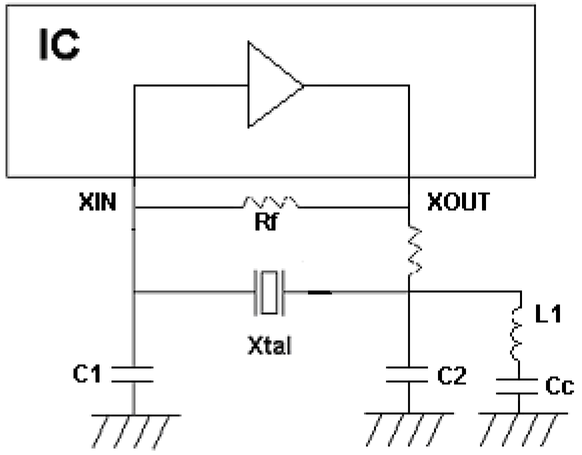


Figure 10. Third Overtone Mode Oscillation Circuit

3. In a standard overtone mode, C2 value varies from 10pF to 30pF. Cc value should be chosen at least 10 times the value of C2, so its equivalent C equiv. will be approximately the value of C2.
4. Typical values of Ll for different crystal frequencies:

25 MHz 4.7uH, 6.8uH, 8.2uH, l0uH
32 MHz 2.7uH, 3.9uH, 4.7uH, 5.6uH
40 MHz 1.5uH, 1.8uH, 2.2uH, 2.7uH, 3.3uH

Negative Resistance
For optimum performance, it is recommended to measure the negative resistance of oscillation circuit. As Fig. 11 show below, raise one end of the crystal from the oscillation circuit and insert a variable resistor beginning with a low value. Monitor the waveform with the oscilloscope, and continue increasing the value of inserted Vr (Variable Resistor), until the circuit will show no oscillation signal on oscilloscope. The value at which oscillation stops represents negative resistance. It is recommended that the negative resistance value of the oscillation circuit should generally be at least five ~ ten times of ESR max.

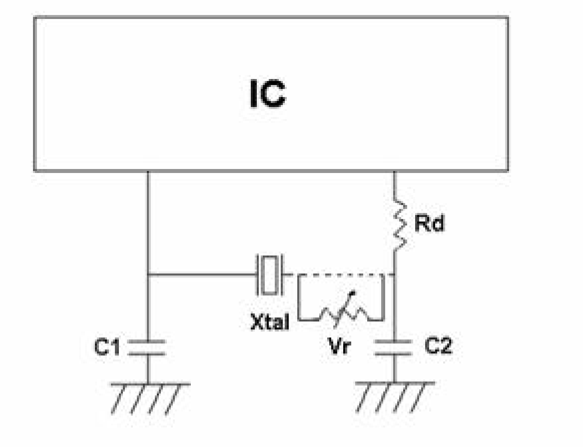


Figure 11 Negative Resistance Measuring