Crystal Resonator Terminology

Acceleration Sensitivity

This property of the resonator (also called g-sensitivity) is the dependence of frequency on acceleration, usually observed as vibration-induced sidebands. Under acceleration, the elastic constants of the quartz blank change very slightly due to elastic nonlinearly; at the same time, the blank deforms minutely. The combination produces small resonator frequency changes with acceleration-induced strain. Since the strain depends on acceleration direction and magnitude, acceleration sensitivity is a vector property. Acceleration sensitivities of typical resonators range from as low as 2×10^{-10}/G to 3×10^{-9}/G, where G is the gravitational acceleration unit. Generally, yield will decrease markedly at the lower end of this range. Over-specification of this parameter or of the vibration environment in which it must be met will greatly increase difficulty of manufacture.

The mechanisms of acceleration sensitivity and the conditions required for zero sensitivity are now well understood. But achieving low sensitivity requires a careful balance of parameters having opposite effects. So far, a truly robust design, in which very low acceleration sensitivity is achieved with practical fabrication tolerances, has not been found.

Acceleration sensitivity also depends to some degree upon the acceleration spectrum. This can be observed in vibration testing using either random vibration or swept frequency sinusoidal vibration, and is due to mechanical resonances of the crystal blank and its mounting structure. These resonances range from a few hundred Hertz in some instances to tens of kHz. Design solutions to most resonance problems are available.

Activity Dips

A sharp increase in resistance occurring over a narrow temperature range when the temperature of a resonator is varied. Historically, resonators were tested in oscillators where an increase in resistance caused the level of oscillation (activity) to decrease (dip); hence the name. Resonators are now more commonly tested in measurement systems that display resistance, but the name persists.

A deviation of the f-T characteristic from a smooth curve accompanies the activity dip, but is often much less pronounced than the resistance increase. In oscillators the resistance increase may cause oscillation to stop over a range of temperature in extreme cases. Activity dips are usually caused by coupled modes but may occasionally also result from small amounts of moisture in the resonator package, in which case they are often called moisture dips.

The frequency of a mode causing an activity dip generally depends upon lateral dimensions; consequently, activity dips are sensitive to small dimensional changes, which may make their control difficult. Moreover, in most cases there is no theory with sufficient accuracy for design, which leads to reliance on empirical methods. For reasons, which are not yet understood, SC-cut resonators typically have fewer such activity dips than AT-cuts.

Aging

Slow changes in resonator frequency with time. Aging is attributable to the relaxation of strain in the resonator and its mounting structure and to mass transfer mechanisms within the resonator package associated with contamination. These factors are minimized by design considerations, including the mechanical design of the mounting structure, and by the design and control of certain manufacturing processes.

Antiresonance Frequency (fa)

In the vicinity of an isolated mode of vibration, the impedance of a crystal resonator is a pure resistance at two frequencies. The greater of these is the antiresonance frequency. (The lower is the resonance frequency, fr. For zero loss the antiresonance frequency is called parallel resonance, fp.

Capacitance Ratio

The ratio of shunt capacitance to motional capacitance.

$$r = \frac{C_0}{C_1}$$

Coupled Modes

An unwanted mode which couples mechanically to the desired or *main* mode, causing an activity dip. At some temperature the unwanted mode coincides in frequency with the desired mode, thereby causing an increase in the resonator equivalent resistance at that temperature. This is referred to as an activity dip. The offending coupled mode is often a high overtone of some low frequency mode such as face shear or flexure, having a large frequency-temperature coefficient. Usually the mode is not electrically excited by the resonator electrodes and can be detected only by its influence on the main mode when the two mode frequencies are nearly coincident. Since there are many such low frequency modes, over a wide temperature range a resonator may have more than one activity dip. Mode coupling mechanisms may be either linear or nonlinear. Linear coupling causes an increase in resistance that is independent of drive level but is very sensitive to temperature. With nonlinear coupling, resistance changes are very sensitive to drive level. Resistance changes which occur at high drive levels may be completely absent at lower levels. Unlike linear coupling, nonlinear coupling can, and in fact often does, occur with other modes of the same family as the desired mode. Since modes of the same family have very similar f-T characteristics, the associated mode coupling shows little dependence upon temperature.

Equivalent Circuit

An R-L-C circuit representing the immittance of a crystal resonator in the vacinity of an isolated mode of vibration. For most purposes, the two-terminal equivalent circuit consisting of the static capacitance C0 in parallel with the dynamic or *motional* branch, L1-C1-R1, is used.
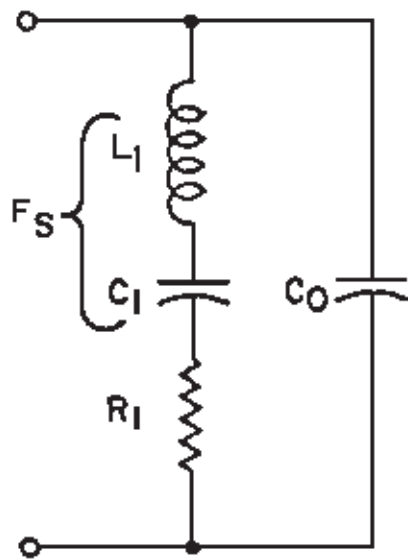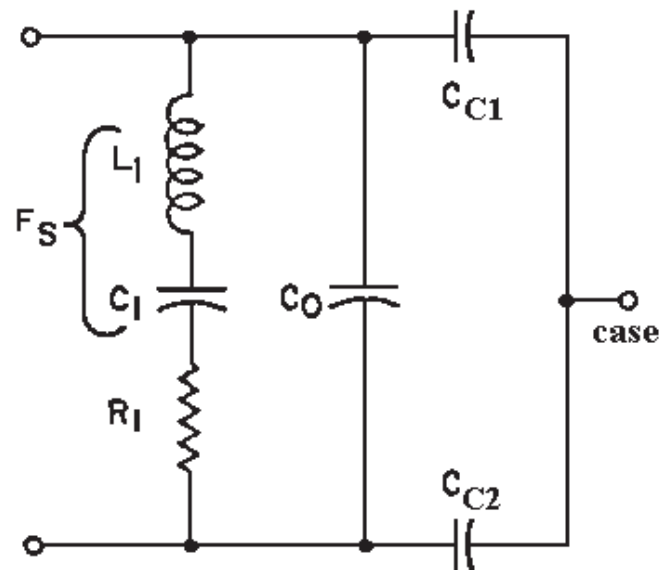
Figure 1a: Two-Terminal Equivalent Circuit

Figure 1b: Three-Terminal Equivalent Circuit

For resonators having metal packages, the three-terminal circuit more accurately represents the holder capacitance. If needed, other electrically excited modes, including unwanted modes, may be represented as additional motional branches in parallel with the L1-C1-R1 branch in either of these circuits.

Drive Level

The level of excitation of the resonator is usually specified in terms of current through the resonator or power dissipated by the resonator. The former is preferred. Drive level should be held to a minimum to avoid problems with stability, aging, nonlinear coupled modes and other nonlinear effects. However, the phase noise floor of an oscillator is reduced by increased drive level, so a compromise is sometimes required.

Figure of Merit

The figure of merit is a useful indicator, particularly for oscillator applications. For M less than 2, the crystal reactance is nowhere positive (inductive). In an oscillator, for a resonator with M less than 2, the sustaining circuit must present an inductive impedance to the crystal unit. For M less than 2, the immittance circle never crosses the real axis of the Smith chart; fr and fa do not exist. At M=2, the immittance circle is tangent to the real axis; i.e., fr=fa. As M increases beyond 2, fr and fa separate and, for large M, approach fs and fp, respectively. In general, the larger M is the more useful the resonator.

$$M = \frac{Q}{r} = \frac{1}{2\pi \cdot f_s \cdot C_0 \cdot R_1}$$

Parallel Resonance Frequency

The frequency of antiresonance in the lossless case. In most cases it is essentially equal to the frequency of antiresonance in the actual case. To a very good approximation,

$$f_p = f_s \left(1 + \frac{C_1}{2 \cdot C_0} \right)$$

Hysteresis

The dependence of resonator frequency at a specific temperature on the prior temperature history of the resonator. As a consequence of hysteresis, the frequency vs. temperature curves obtained by slowly increasing the temperature from, say, -55°C to +85°C will not coincide with the curve obtained by slowly decreasing the temperature from +85°C to -55°C as reflected in Figure 2.
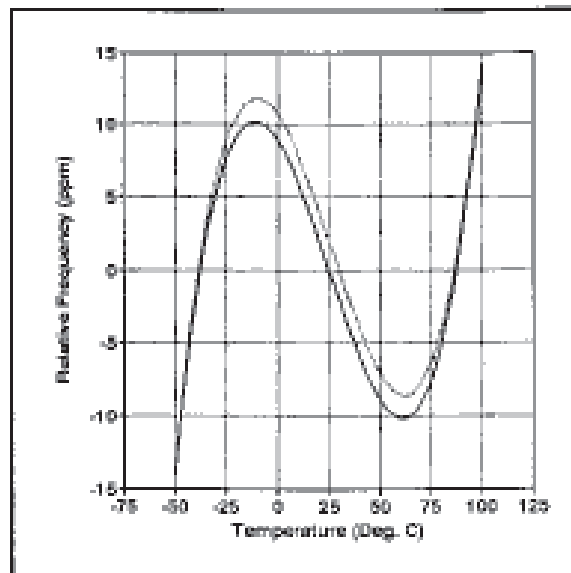
Hysteresis is particularly important in tight-tolerance TCXOs and in MCXOs. True hysteresis is a static effect. In measuring hysteresis, great care must be used to avoid temperature gradients, which produce an apparent hysteresis of frequency, especially for AT-cut resonators.

Load Capacitance (CL)
A capacitance in series with a resonator to provide a method of frequency adjustment, especially in an oscillator circuit.

Load Frequency (fL)
The resonance frequency of the series combination of a resonator and a load capacitor.

$$\frac{f_L - f_s}{f_s} \approx \frac{C_1}{2 \cdot (C_0 + C_L)}$$

Load Resistance (RL)
The effective resistance, at fL, of the resonator in series with the load capacitance. This resistance is given by the following approximate expressions:

$$R_L \approx R_1 \cdot \left(1 + \frac{C_0}{C_L}\right)^2 \qquad\qquad \frac{R_L}{R_1} \approx \left(\frac{C_0 + C_L}{C_L}\right)^2$$

Moisture Dips
Activity dips caused by moisture condensation on the resonator blank (usually near 0°C). They result from poorly sealed or incompletely purged packages or from defective package headers. Although historically quite common, moisture dips are easily avoided with adequate process control. Proper f-T measurement and careful leak detection inspection are important aspects of moisture dip quality assurance. On rare occasions, mishandling of parts may cause leaks in lead seals resulting in moisture dips.

Motional Capacitance (C1)
An element of the motional impedance arm of the resonator equivalent circuit which, in combination with L1, is resonant at fs.

Motional Inductance (L1)
An element of the motional impedance arm of the resonator equivalent circuit which, in combination with C1, is resonant at fs.

Motional Resistance (R1):
The element of the motional impedance arm of the resonator equivalent circuit representing energy loss.

Motional Resonance Frequency (fs)
The frequency of resonance (zero reactance) for the motional arm of the equivalent circuit.

$$f_s = \frac{1}{2\pi\sqrt{L_1 \cdot C_1}}$$

Nonlinearity
The dependence of equivalent circuit element values on excitation level. Quartz resonator nonlinearity is manifested in a variety of ways. These include change in resistance with drive level, including high resistance at low current, excess phase noise, change in frequency with drive level, and coupling to other modes at high drive level.

For precision applications, resonator nonlinearity must be considered. There are three sources of nonlinearity. Depending on resonator current, one of the three is usually dominant, although, strictly speaking, the three coexist. At low current levels, the most important effect is anomalous motional resistance, generally high resistance at low current, often decreasing at higher current, accompanied by hysteresis and lack of repeatability. In an oscillator, low-level nonlinearity may be exhibited as a failure of the oscillator to start. Low-level nonlinearity is sometimes called "sleeping sickness" or "second level of drive". Its cause is generally resonator surface condition, which can be controlled through design and control of manufacturing processes. At somewhat higher levels, elastic nonlinearity comes into play, causing the resonance frequency to change

with current, an effect known as nonlinear resonance. (Crystalline quartz is known to exhibit a small but significant elastic nonlinearity.) For AT- and SC-cut resonators, frequency increases with current; for some other cuts, it decreases. In addition, heating due to I²R loss in the resonator must occasionally be considered, but this problem is not common in modern applications. Nonlinear coupling to other resonant modes may complicate nonlinear resonator behavior. The nonlinear effects in resonators have their counterparts in the performance of crystal filters, where nonlinearity produces intermodulation, frequency shift and variation of insertion loss with signal level, and excess phase noise.

Pullability

The change in the load frequency, fL, due to a change in the load capacitance, CL. A convenient measure is the pulling sensitivity, S.

Pulling sensitivity

If C1, C0 and CL are all in the same units, then S is:

$$S = \frac{10^6 \cdot C_1}{2 \cdot \left(C_0 + C_L\right)^2} \; \frac{ppm}{pF}$$

Quality Factor

The quality factor of a reactive component. In a crystal resonator it is the reactance X1 of the motional inductance or capacitance divided by the motional resistance R1.

$$Q = \frac{|X_1|}{R_1} = \frac{2\pi \cdot f_s \cdot L_1}{R_1} \quad \text{or} \quad \frac{1}{2\pi \cdot f_s \cdot C_1 \cdot R_1}$$

The maximum Q which can be obtained is determined by several additive loss factors, the first of which is the intrinsic Q of quartz, which is approximately 16 x 106 divided by the frequency in MHz for the AT-cut, and slightly higher for the SC-cut. Other factors which further limit the Q are mounting loss, atmospheric loading (for non-evacuated crystal units) and the surface finish of the blank. Mounting loss depends upon the degree of trapping produced by the electrode and the plate diameter. The highest Q is obtained by using mechanically or chemically polished blanks with an adequately large diameter and an evacuated enclosure. A typical 10 MHz, 3rd overtone SC may have a Q of 1.0 to 1.3 million; a 100 MHz, 5th overtone AT may have a Q of 80 to 100 thousand, while a 100 MHz AT fundamental would be much lower, in the range of 20 to 50 thousand.

Resonance Frequency (fr):

In the vicinity of an isolated mode of vibration, the impedance of a crystal resonator is a pure resistance at two frequencies. The lower of these is the resonance frequency. (The greater is the anti-resonance frequency, fa). Because of the shunt capacitance, C0, fr is greater than fs. For resonators with a large figure of merit (M>5), fr can be approximated by:

$$\frac{f_r - f_s}{f_s} \approx \frac{1}{2 \cdot Q \cdot M} \qquad f_r \approx f_s\left(1 + \frac{1}{2 \cdot Q \cdot M}\right)$$

Resonator Resistance (Rr)

The resistance of the resonator at its frequency of resonance, fr. Rr differs from, and is larger than, the motional resistance, R1 because of the presence of C0, but for resonators with a large figure of merit (M>5), it is essentially the same as R1.

Radiation Hardness

The ability of quartz resonators to withstand ionizing radiation, which causes transient or permanent changes in resonator frequency and resistance related to dose rate and total dose. Resonators are also affected by neutron fluence. Radiation hardness is of importance principally in certain weapons system applications and satellite applications. Sweeping is used to improve the radiation hardness in these applications.

Shunt Capacitance (C0)

The element in the resonator equivalent circuit representing the electrostatic (parallel-plate) capacitance of the electrodes plus the holder capacitance. Shunt capacitance is also called static capacitance.

Sweeping

A solid-state electrolysis process which removes certain impurities from as-grown quartz, improving radiation hardness, aging and Q. Sweeping also improves the etch characteristics of quartz and is an essential process in making high frequency fundamental resonators. The process requires the application of a high electric field, typically 1000 V/cm, at a high temperature, typically 500°C.

Unwanted Modes ("Spurs")

Resonant modes in addition to the desired mode. Although only one resonant branch is shown in the equivalent circuit of Figure 1a, many other resonances exist, some of which are excited by the electrodes and can be represented by additional L-C-R circuit branches in parallel with the main branch. These are commonly called unwanted modes or spurs. Of these, the family of anharmonic (non-harmonically related) unwanted modes associated with and slightly higher in frequency than the principal mode is particularly important. Other families of unwanted modes also exist. Unwanted modes are of particular concern in filters, where they typically cause sharp unwanted responses (spurs). In oscillator applications it is essential that the desired mode have lower resistance than all other modes in a frequency range determined by the sustaining circuit bandwidth in order to assure that the oscillator always operates on the desired mode and does not jump to an unwanted mode. When a strong unwanted mode cannot be suppressed, mode selection or mode trap circuits must be used in the oscillator. In VCXOs, unwanted modes may limit the usable tuning range. Unwanted modes are usually specified in terms of resistance or in terms of the ratio of resistance of the unwanted mode to the resistance of the main mode over a suitable frequency range. For oscillator crystals, a ratio is the preferred method of specification. A resistance ratio of 2:1 is usually adequate. For filter applications, the mode resistance itself is the proper parameter to specify. Mode resistance is sometimes specified indirectly in terms of the attenuation in a transmission network, which must be fully specified.

The AT- and SC-cuts have three families of thickness type modes identified as A, B and C, the latter being the commonly used main mode in AT- and SC-cut resonators. Indeed, in AT-cuts, the A and B mode families are not excited by the usual electrodes, and so cause no problems. In SC-cuts, in addition to the C mode, the A and B modes are excited. Furthermore, B has a frequency approximately 1.1 times the C mode frequency and its resistance is usually about the same as the C mode resistance. Currently, B mode oscillation is prevented by using a mode suppression circuit but techniques now being studied to increase the ratio of B mode to C mode resistance may make this unnecessary at some future time.