Application Note

Specifying Quartz Crystals

Quartz crystals are available in a myriad of shapes and sizes, and can range widely in performance specifications. These specifications include *resonance frequency, resonance mode, load capacitance, series resistance, holder capacitance, motional inductance and capacitance*, and *drive level*. Understanding these parameters and how they relate to the crystal's performance will allow you to successfully specify crystals for your circuit application.

A quartz crystal can be modeled as a series LRC circuit in parallel with a shunt capacitor. Figure 1 shows this generic circuit model.

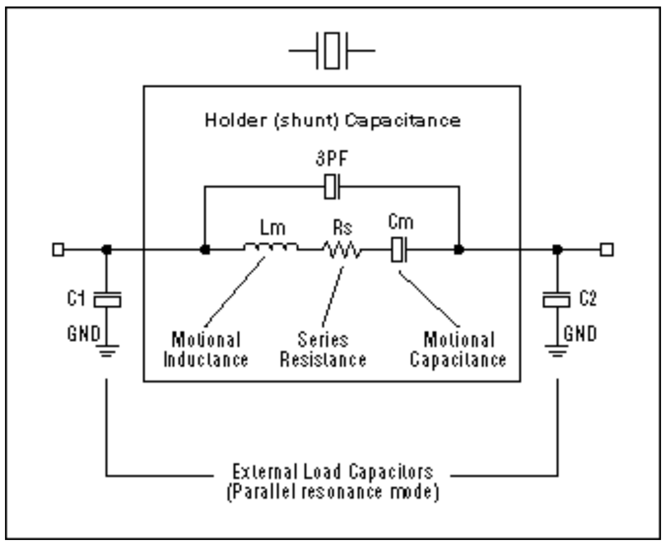

Figure 1. Generic crystal model (fundamental mode)

Now let's look at each key performance specification in detail.

Resonance Frequency

Crystals below 30MHz are often specified at the fundamental frequency, but above 30MHz they are typically specified as 3rd, 5th, or even 7th overtone (overtones occur only at odd multiples). It's important to know whether the oscillator is operating in *fundamental* or *overtone* mode. An overtone is similar in concept to a harmonic, with the exception that crystal oscillation overtones are not exact integer multiples of the fundamental. Selection of overtone is based upon using the lowest possible overtone that will result in a crystal fundamental frequency below 30MHz. The vendor calibrates a 3rd overtone crystal at the 3rd overtone, not the fundamental. For example, most crystal vendors will automatically give you a 3rd overtone 50MHz crystal if you don't specify fundamental mode or an overtone mode. If you plug a 50MHz 3rd overtone crystal into an oscillator that expects a fundamental−mode crystal, you are likely to have an oscillator running at 50/3 or 16.666MHz! If you don't know the frequency mode of your crystal, contact the designer or the manufacturer of the oscillator circuit.

The reason crystal vendors provide overtone crystals is that the quartz material becomes thinner and thinner as frequency increases. Starting at about 30MHz, the quartz becomes so thin that it is hard to handle during the manufacturing process, and crystal vendors don't like to deal with thin crystals. One recent innovation in this area is the invention of *inverted mesa* crystals. Inverted mesa crystals can be manufactured with a thinner structure and thus can be reliably manufactured at higher fundamental−mode frequencies. This makes for less complex high−frequency oscillator designs and reduces component count by avoiding the need for external inductors/capacitors to induce the proper overtone oscillation mode from the crystal. Not all crystal vendors can provide inverted mesa technology; but, for the ones that can, they will be able to specify fundamental−mode crystals considerably higher than 30MHz. Remember that an overtone−mode *crystal* cannot be used in a fundamental−mode *oscillator,* and vice versa. It may oscillate but not at the correct frequency.

Resonance Mode

Crystals have two modes of resonance: *parallel* and *series.* All crystals exhibit both resonance modes. The oscillator circuit is calibrated for one or the other, but not both. For applications requiring no tighter than 100ppm frequency accuracy, this spec is usually not an issue. However, if you are attempting to control frequency (or time) to within 100ppm, the resonance−mode specification becomes important. The difference to the crystal vendor is in which mode the crystal is calibrated during manufacturing. The crystal vendor sets up an oscillator circuit with the crystal in a customer−specified series resonance or parallel resonance and calibrates the crystal. Figure 2 shows crystal impedance behavior versus frequency as well as the relative location of each resonance mode.

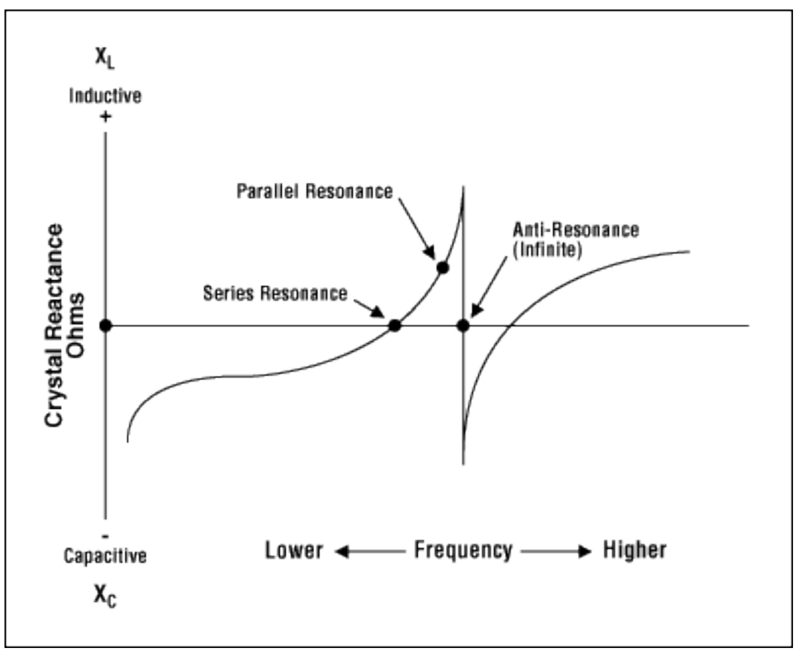

Figure 2. Crystal impedance versus frequency

Load Capacitance

Load capacitance is an important specification when using parallel resonant oscillation mode. Referring to Figure 2, it can be seen that crystal parallel resonance mode is always above the series resonance frequency and is characterized by inductive reactance. In parallel resonance oscillation mode, the crystal's inductance (motional inductance) is in parallel with the oscillator's load capacitance, thereby forming an LC tank circuit. This LC determines the oscillator frequency. If your oscillator uses parallel resonance, the crystal vendor must know the load capacitance employed by the oscillator circuit. The load capacitance is simply the amount of external circuit capacitance in parallel with the crystal itself when it is placed in the oscillator circuit. The crystal vendor will then make sure that your crystal is calibrated at the factory using this same load capacitance. Vendors are flexible regarding load capacitance; ask them what range of load capacitance you can specify. Your oscillator should fall within the crystal vendor's acceptable range of load capacitance.

With a series resonant crystal, you can ignore the load capacitance specification, because the motional inductance and motional capacitance of the crystal are the only LC components that determine oscillation frequency.

In Figure 2, the anti−resonance occurs when the net inductive component of the crystal model resonates with the crystal's internal holder capacitance. Anti−resonance is not used for oscillator designs.

Series Resistance

Series resistance is the effective resistive component in series with the LC model of the crystal itself (see Figure 1). Oscillator circuits can tolerate a certain degree of series resistance but not too much. A typical range is 25 ohms to 100 ohms for most crystals. The crystal vendor usually characterizes this resistance and specifies typical or maximum values for series resistance. Excessive crystal series resistance can lead to oscillator startup failure, so sufficient margin must be built into the oscillator design.

An exception is 32.768KHz wristwatch crystals. Their series resistance can be in the tens of kilohms, so the oscillator circuit must be designed to accommodate this high series resistance. Failure to address this will result in a 32.768KHz oscillator that does not oscillate. Don't expect to use an oscillator designed for a 10MHz crystal with a 32.768KHz crystal; it won't work.

Holder Capacitance

All crystals have small electrodes that connect the crystal to the package pins. The electrodes form a shunt capacitance in parallel with the crystal's LC model, as shown in Figure 1. Depending on the crystal's size and package, the holder capacitance can vary. Typical values range from 2pF to 6pF. Some oscillators will not tolerate excessive holder capacitance. This is particularly true at higher frequencies as the reactance of the holder capacitance decreases. Make sure the crystal vendor's holder capacitance is within the allowable range for your oscillator. As a general rule, minimize the holder capacitance (the smaller, the better).

Motional Inductance and Capacitance

Motional inductance and capacitance are specifications provided by the crystal vendor. They describe the L and C values that comprise the electrical LC model of the crystal. What is noteworthy about these values is the extreme ratio of L to C, which results in very large inductive and capacitive reactance values at the operating frequency. This is what gives a crystal its extraordinarily high "quality factor," also referred to as "Q" (Q being the ratio of energy stored to energy dissipated, also defined as the ratio of reactance to series resistance at the resonant frequency). For an LRC circuit, Q = 1/R * sq. rt. (L/C) (the derivation of this is beyond the scope of this article). A high Q is desirable. Higher Q values mean less frequency shift for a change in oscillator load capacitance and less shift due to other external factors such as oscillator supply voltage. Depending on your application, your oscillator circuit may or may not require specification of motional inductance and capacitance.

Drive Level

The power dissipated in the crystal must be limited or the quartz crystal can actually fail due to excessive mechanical vibration. Crystal characteristics also change with drive level due to nonlinear behavior. Analyze the oscillator design to determine the power dissipated in the crystal. Power dissipated is the product of *crystal current squared* times crystal series resistance. For a parallel resonant oscillator, the crystal current equals the RMS voltage across the load capacitor divided by the load capacitor's reactance at the oscillator frequency. For a series resonant crystal, the crystal current is the RMS voltage across the crystal divided by the crystal internal series resistance. The crystal manufacturer will specify maximum drive levels for a particular product line.

Expect crystal usage to continue to increase as crystals find their way into more and more products that use microcontrollers, digital signal processors, and data converters. Crystal technology is also moving forward, resulting in better performance and lower costs. Though at first glance, crystals may seem simple elements that one merely plugs into the circuit, an analysis of the actual circuit model and an understanding of key parameters show them in a different light and also simplify the process of designing them into your next application. The following handy crystal specification worksheet will help you in specifying and ordering quartz crystals.

Table 1. Crystal Specification Worksheet

Parameter	Value	Comments
Frequency		Above 30MHz specify overtone number
Resonance Mode		Specify parallel or series
Load Capacitance		Check with oscillator designer/vendor
Series Resistance		Specify MAX value (get from osc. designer)
Holder Capacitance		Crystal manufacturer will provide
Motional Inductance and Capacitance		Varies with manufacturer
Drive Level		Typically a MAX number from crystal vendor

Table 2. Partial List of Crystal Vendors

Company	Toll−Free Number	Contact Number	Website Address	City, State (USA)
International Crystal Manufacturing (ICM)	(800) 725−1426	(405) 236−3741	www.icmfg.com	Oklahoma City, OK
Jan Crystals	(800) 526−9825	(813) 936−2397	www.jancrystals.com	Ft. Meyers, FL
ECS International	(800) 237−1041	(913) 782−7787	www.ecsxtal.com	Olathe, KS

CTS Reeves Frequency Products		(815) 786−8411	www.ctscorp.com	Sandwich, IL
CTS Reeves Frequency Products		(717) 243−5929	www.ctscorp.com	Carlisle, PA
Crystal Works, a Division of Connor Winfield		(405) 273−1262	www.conwin.com www.crystal−works.com	Shawnee, OK

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