Design Choice: Crystal vs. Crystal Oscillator

ABSTRACT

When doing a new design that requires controlled timing, a common consideration is to determine if the timing device is to be a crystal or an oscillator. This Application Note compares the design and operational impact of this choice. It also considers the use of crystals and oscillators from the KHz range to over 1GHz.

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1 DESIGN CONSIDERATIONS FOR USING A CRYSTAL

The crystal only provides the frequency selective element in final application. There are external components required, and a gain stage is needed to achieve the final required clock signal. The crystal frequency range is normally considered to be less than 160MHz. Crystals above this frequency require complex circuit designs with difficult tuning and specialized high frequency crystals.

1.1 GAIN STAGE

A CMOS or a BJT gain stage needs to be provided, there are many accepted configurations. The input and output impedance of this stage affects the circuit Q. The amplifier noise level impacts both the phase noise and jitter. How this stage biases in the active gain region is critical for oscillator startup. Also, the bandwidth of this stage affects the startup characteristics. If the oscillator circuit is to operate the crystal on an overtone, then a frequency selective device is needed in the amplifier circuit to assure the circuit only has the needed gain and phase shift at the desired crystal overtone.

1.2 CRYSTAL DRIVE LEVEL

The oscillator circuit results in AC current at the resonance of the crystal. This AC current or drive level has to be below a critical value or a crystal can be damaged. Excessive current can cause the crystal motion to exceed the elastic limit and fracture. The XY cut (tuning fork) 32.768KHz watch crystal has to be limited to about 5µA or less or the tines of the crystal will fracture.

The crystals >1MHz are typically AT cut crystals. These devices are tolerant of a wide drive level range. Fracture will not occur until milliwatt drive levels are reached. Added aging can occur in the higher µW drive ranges. Over driving the crystal can excite unwanted modes of vibration. These can result in severe frequency jumps over vary narrow temperature ranges.

1.3 C_{LOAD} VALUE

In most cases, crystals are operated with a reactive load. This permits adjustment of the final frequency in the final application. This is often needed to correct for the frequency change versus time of the crystal. The C_{LOAD} value determines the frequency versus load capacitance sensitivity. AT cut crystals can have a sensitivity of 30ppm/pF for low values. Using higher values of load capacitance reduces sensitivity but increases the difficulty of startup of oscillation. The C_{LOAD}'s temperature characteristics can change the frequency versus temperature response of the oscillator.

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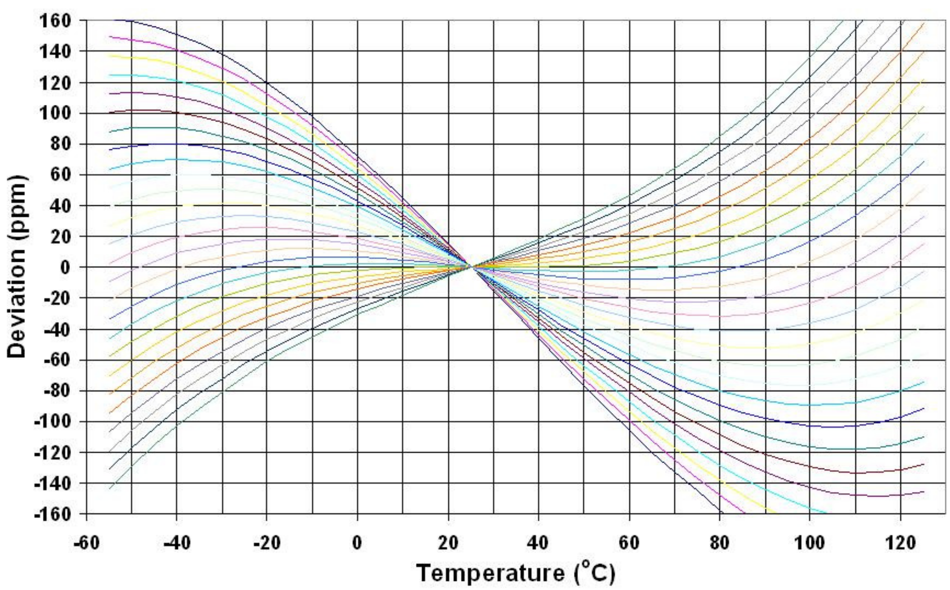
1.4 FREQUENCY TEMPERATURE CHARACTERISTICS

The frequency response of the crystal is determined by the cut of the crystal through the atomic planes of the quartz crystal. This results in a stable and repeatable temperature response. The graph shows the frequency temperature response for different cuts of the AT cut crystal. Each curve is 2 minutes of arc different.

The C_{LOAD} temperature coefficient can alter this response by many minutes The C_{LOAD} value and the capacitor is critical for the oscillator to meet the desired characteristics. The C_{STRAY} of the amplifier and the amplifier phase shift change vs. temperature both impact the frequency temperature characteristics.

1.4.1 FREQUENCY vs. TEMPERATURE FUNCTION OF AT CUT CRYSTALS



Each curve is a variation of 2 minutes of arc of the cut through the atomic planes of the quartz crystal.

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1.5 SPECIFYING THE CRYSTAL AND INCOMING INSPECTION

The crystal has many parameters that should be specified to assure receiving a device that meets the end application requirement.

- Frequency
- Calibration, set point at 25°C
- C_{LOAD}
- Stability, frequency versus temperature referenced to 25°C
- Operating temperature range
- Maximum ESR of CI, crystal resonant resistance
- C_0 range, the pin-to-pin capacitance
- $L_{MOTIONAL}$ or $C_{MOTIONAL}$, sets the pullability of the crystal
- Drive Level
- Drive Level Dependency (DLD) of both frequency and resistance
- Aging
- Insulation resistance

There are other specifications, such as maximum allowed frequency change per °C, or the maximum allowed response from a smooth curve (perturbation control).

Incoming inspection or testing requires specialized equipment:

- Crystal Impedance Meter (CI Meter)
- Network analyzer with special test fixtures and software

1.6 PWB/PCB LAYOUT

Board layout is critical to achieve best performance. Here are some of the considerations:

- Lead lengths must be as short as possible.
- The leads to the crystal are high impedance and very sensitive to noise.
- The ground node of the capacitors and the crystal package must not involve circulating currents of noise sources.
- If the leakage path on the leads is lower the 500K ohm, this can affect oscillator start up and will also shift the frequency as much as a few ppm.

1.7 SUMMARY

When a crystal is used to set the frequency of an end user supplied oscillator, there are many considerations and design parameters that must be done to assure the optimum performance.

See our Application Note 810 for more on the design considerations and selection of C_{LOAD}.

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2 DESIGN CONSIDERATIONS FOR USING AN OSCILLATOR

The oscillator includes all the considerations stated in 1-1.7 for use of a crystal. Fortunately, several of the complexities for operating with a crystal can be easily resolved when using an oscillator.

- The oscillator has an unfinished crystal installed and during the final part of the process, the crystal has its frequency calibrated at room temperature.
- The crystal is matched to the temperature coefficients of the oscillator circuit. The crystal angle or cut is changed to offset the oscillator circuits' temperature coefficients.
- The leads to the crystal are normally then sealed in the hermetic crystal package to minimize any chance that the end use can alter the oscillator performance.

Testing or validating an oscillator's performance is easily done with an oscilloscope, frequency counter and a power supply.

2.1 COMPARISON OF APPLICATIONS USING A CRYSTAL vs. AN OSCILLATOR

Specification	CRYSTAL	OSCILLATOR
Initial Frequency Setting	End user is responsible for setting crystal C_{LOAD}, often requiring setting to <0.3 pF tolerance to achieve required set point	The oscillator has the temperature and C_{LOAD} matched to the crystal. During oscillator fabrication, the initial frequency setting is automatically adjusted, thereby compensating for all oscillator component effects.
Frequency vs. Temperature	End user chooses components that do not change the crystals frequency vs. temperature characteristics. The crystal makers assume a zero temperature coefficient of C_{LOAD}. Crystals should be ordered given the temperature characteristics of the oscillator circuit so the crystal angle can be adjusted.	
Oscillator Startup	End user is responsible to determine the needs of the oscillator circuit applied to the crystal. This includes any drive level dependencies (DLD) and ability to tolerate some amount of DLD.	Specified in the datasheet. Part of the oscillator design.
Aging	End user is responsible for component changes with time in addition to the specified crystal aging, such as oscillator C_{LOAD}. Oscillator gain changes aging.	Specified in the datasheet. Part of the oscillator design.
System Jitter (Phase Noise)	End user must optimize all parts of the oscillator design, operate the crystal at the best drive level, be concerned with all component noise levels, be sure to optimize the in-circuit crystal Q and isolate the resonant circuit from any load changes. All nodes of the oscillator on the PWB/PCB are sensitive to coupled noise.	Specified in the datasheet. Part of the oscillator design. Oscillator packaging normally shields the device from system noise injection. End user must supply a noise-free power supply signal with supply lead bypass.

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Specification	CRYSTAL	OSCILLATOR
PWB/PCB Cleanliness	All leads around the crystal must be kept clean and contaminant free. The nodes at the crystal have low impedance for MHz range crystals and high impedance for kHz range crystals. Industrial applications using watch crystals require conformal coating of the leads and capacitors around the crystal.	Many oscillators today are hermetically sealed, protected from any process contamination and sealed from any end-use dust and moisture.
Shock and Vibration	Resonator sensitivity the same for both crystals and oscillators. Micro phonics of all components in the resonant circuit must be considered.	Resonator sensitivity the same for both crystals and oscillators. The datasheet defines the sensitivity. Micro phonics are minimized by today's miniature oscillator packages.
Repair/ Replacement of Timing Device	If components are to be replaced, then full specification of each part must be known as they all impact the precision of the oscillator vs. time and temperature. To repair and retain the designed-in precision can be difficult if any component is replaced, especially the crystal. The required temperature coefficients are seldom documented in the repair manuals.	Simple to repair, replace with matching part number.
EMI/ RFI	Dependent on the circuit design, component selection and PWB/PCB design.	Normally supplied in a grounded package to minimize EMI/RFI.
Cost	Less Costly	More Costly