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Make Your Next Design Solid As A Rock

Crystal oscillators sustain the heartbeat for virtually all electronic products.

In fact, some multiprotocol networking and telecom equipment can contain 10 or more different crystals.

A crystal oscillator usually sets the processor clock frequency and operational frequencies of networking speed or wireless channels. Crystals provide the accurate timing required by most modern products, in addition to the precision demanded by the FCC in setting operational wireless and networking frequencies.

When designing your products, you can opt to make your own crystal oscillator or design in one of the many available pre-packaged crystal oscillators. In some cases, all you do is connect the appropriate crystal (plus two capacitors) to the processor or other chip, which has the oscillator circuitry built in. Other cases require a separate oscillator.

In these instances, investing the development time and money in designing and building your own crystal oscillator no longer makes economic or time-to-market sense. Electronic design today is more about putting together components and chips to form a system rather than creating detailed circuits. Now, crystal oscillators have evolved into an off-the-shelf subsystem component.

THE MAGIC CRYSTAL

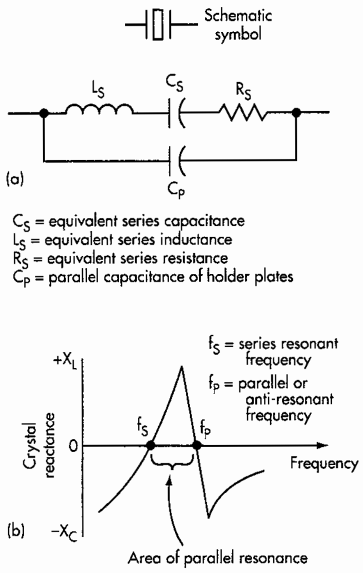
Crystal oscillators are virtually mandatory in more complex modern electronic products. Made of pure quartz, these thin slivers vibrate at a precise and very stable frequency. Their ability to be set to almost any desired frequency and maintain that frequency over a wide range of temperature and voltage variations makes them inordinately better than any RC or LC oscillator.

Quartz is a crystalline structure found in nature and the second most common material found in the earth's surface next to feldspar. Its chemical composition is silicon dioxide (SiO_2), but its piezoelectric characteristics make it special.

Piezoelectricity is a material's ability to generate a voltage when stressed mechanically or to vibrate at a precise frequency if excited by a voltage. This latter characteristic makes quartz the frequency-determining component of choice for most applications.

While quartz crystals are readily found in nature, they can be synthesized. Pure quartz crystal is formed by melting a mined material called lasca in an autoclave and using a seed crystal. Such crystals are then cut into slivers and ground to the desired thickness that sets the frequency of operation.

1. The equivalent circuit of a crystal is a series-resonant RLC circuit. The equivalent inductance also forms a parallel resonant circuit with the capacitance of the mounting plates or connections (a). Crystal reactance variation over frequency shows series and parallel resonant points of the crystal (b). These resonant points are very close together. The parallel resonant point is never used because of its instability, but the series frequency and a small range just above it are the main points of operation in most crystals.



The geometry and angle of the slice cut from the crystal determines its stability and other characteristics. Different cuts are referred to by designations such as AT, SC, and X cuts. Two plates of silver are deposited on opposite faces of the crystal, and mounting leads are attached to them. The completed assembly is mounted in an enclosure, usually metal.

The crystal itself looks like a series resonant circuit with equivalent inductive, capacitive, and resistive components *(Fig. 1a)*. Placing the crystal in a holder produces a parallel capacitance, with the crystal serving as the dielectric between the two holding plates. This combination produces a unique circuit with both series and parallel resonances *(Fig. 1b)*.

A crystal may be operated in either its series or parallel or anti-resonant modes, depending on the oscillator circuit used. The parallel mode is usually avoided because it's less stable. However, the frequency range between the series and parallel resonant points is commonly used. This area is known as the parallel mode range.

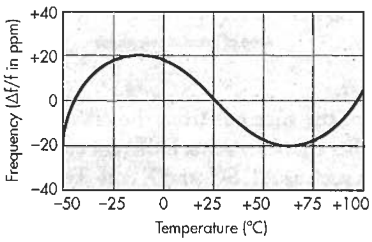
When operating in the parallel mode, the external capacitance across the crystal will determine the operating frequency. Called the load capacitance, this reactance is any stray or distributed capacitance on the printed-circuit board (PCB) and in the oscillator circuit. Usually in the 3- to 20-pF range, it must be specified when ordering a crystal to be used in a parallel-mode circuit.

You can also add a series or parallel capacitor to a crystal to "pull" its resonant frequency over a narrow range. This feature permits minor adjustments to the frequency, as well as the ability to produce a variable-frequency crystal oscillator for use in phase-locked loops (PLLs).

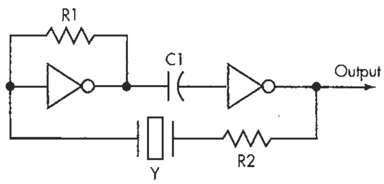
Most crystals also oscillate at higher overtone frequencies. The third and fifth overtones are the most common. An overtone is an approximate third, fifth, or other odd multiple of the primary resonant frequency. A harmonic of a fundamental frequency is an exact multiple, while the overtone is a close but not exact multiple.

Since the fundamental oscillating frequency of a typical crystal is limited to about 30 to 50 MHz maximum, the overtone mode of oscillation is one way to achieve crystal precision and stability at higher frequencies. When specifying an overtone crystal, it's important to stress the exact frequency needed so that the manufacturer can produce the appropriate fundamental frequency in the crystal.

Designers should consider 10 key specifications when comparing and selecting crystal oscillators.



2. A frequency stability curve for a crystal oscillator shows the frequency deviation in ppm versus the change in temperature. Different cuts of crystal produce a wide range of frequency stability curves. The AT and SC cut crystals are the best suited to most applications.



3. A series-mode crystal oscillator uses a loop of two digital inverters, usually CMOS, but TTL has also been used. R1 biases one inverter into its linear range for amplification, while R2 sets the crystal current.

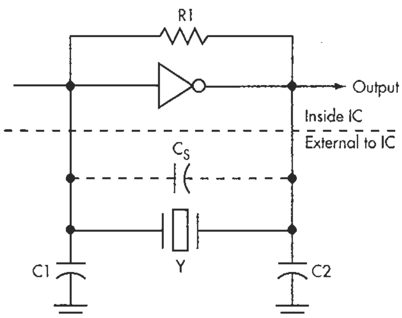
Frequency of operation: Crystal oscillators come in a frequency range of approximately 1 to 70 MHz. Special lower-frequency crystals like the popular 32.768-kHz watch crystal are also available. The physical thinness of the crystal limits the upper frequency range. That limit has gone from about 30 MHz in past years to about 200 MHz, thanks to the development of new manufacturing techniques like the inverted Mesa. The operating frequency is usually stated at a temperature of 25°C.

Higher-frequency oscillators can be obtained by using overtone crystals that take the output to over 200 MHz. In addition, oscillators with built-in PLL frequency multipliers can reach frequencies beyond 1 GHz. When UHF and microwave frequencies are required, the surface-acoustic wave (SAW) oscillator is an option.

Frequency accuracy: Also known as frequency tolerance, frequency accuracy measures how close the crystal frequency is to the desired value as determined by the application. It's often expressed as a percentage deviation from the specified frequency or in parts per million (ppm). For example, an accuracy of ±100 ppm of a 10-MHz crystal oscillator means that the actual frequency could deviate from 10 MHz by ±1000 Hz:

$$(100/1,000,000) \times 10,000,000 = 1000 \text{ Hz}$$

This is the same as 1000/10,000,000 = 0.0001 = 10^{-4} or 0.01%. Typical oscillator accuracies range from 1 to 1000 ppm, stated at an initial temperature of 25°C.



4. A critical specification in parallel-mode crystal oscillators (typical in embedded controllers) is the parallel capacitance C_S, which must be specified when ordering a crystal for this circuit. Values range from a few picofarads to about 40 pF.

CRYSTAL ALTERNATIVES

While most applications will use a crystal oscillator, two options may be a better fit for your design: ceramic resonators and surface-acoustic-wave (SAW) resonators.

Ceramic resonators are piezoelectric components made from materials other than quartz, like lead zirconium titanate (PZT). These devices are smaller than crystals and have a tolerance of about 0.5%, compared to the 0.001% or better tolerance of a quartz crystal. Where precision is only marginally important, a ceramic resonator will work nicely at much lower cost. A common application is the clock in an embedded controller.

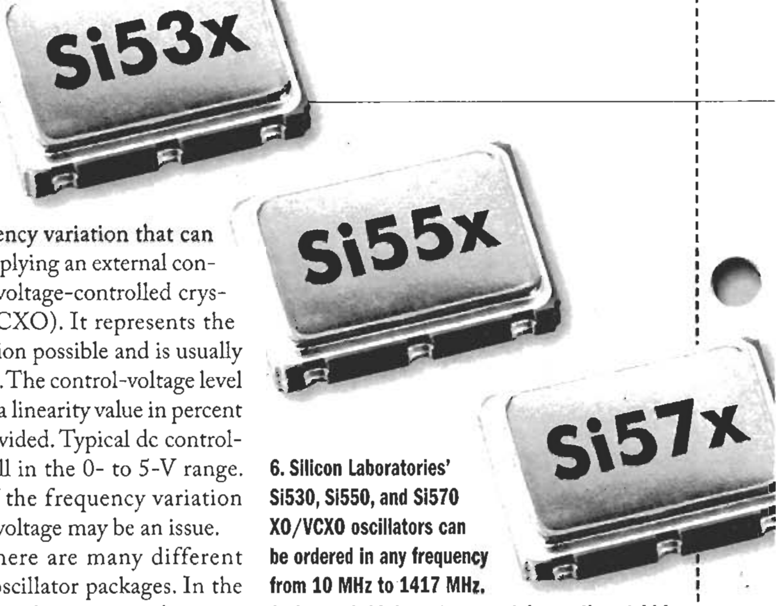
A SAW resonator uses an inter-digital transducer on a quartz substrate. SAW devices are used mostly for UHF/microwave filters, but they can also work as the frequency-determining component in a oscillator. These oscillators usually operate at frequencies in the 300-MHz to 1-GHz range, beyond the range of most crystal oscillators. They can produce good precision (±100 ppm) and low phase noise. ED ONLINE 18165

Very high-accuracy crystals are specified in part per billion (ppb).

Frequency stability: This measures how much the frequency deviates from the desired value over a specific temperature range, like 0°C to 70°C and −40°C to 85°C. The stability is also stated in ppm and varies widely depending on the oscillator type from 10 to 1000 ppm *(Fig. 2)*.

Aging: Aging is the change in frequency over a long period of time, usually measured in weeks, months, or years. It's independent of temperature, oscillator voltage, and other conditions. Most aging frequency change occurs in the first several weeks after the oscillator is turned on. It can be as much as 5 to 10 ppm. After that initial period, the aging frequency change flattens out to a few ppm.

Output: Crystal oscillators are available with different types of output signals. Most are pulse or logic levels, but additionally, there are sine-wave and clipped-sine outputs. Some common digital outputs include TTL, HCMOS, ECL, PECL, CML, and LVDS.



6. Silicon Laboratories' Si530, Si550, and Si570 XO/VCXO oscillators can be ordered in any frequency from 10 MHz to 1417 MHz. An internal third overtone crystal operating at 114 MHz stabilizes a digital VCO running at 5 GHz using a PLL multiplier that incorporates Silicon Labs' patented DSP filtering to provide exceptional jitter performance. The DVCO and a set of output frequency dividers program the output frequency.

Most digital outputs have a 40%/60% duty cycle, but a 45%/55% output is attainable in some models. A tri-state output may also be available in some models. The maximum load is also specified and is usually given as a fan-out number or as a capacitance in picofarads.

Operating voltage: Most crystal oscillators operate from 5 V dc. But newer designs offer 1.8-, 2.5-, and 3.3-V operation.

Start time: This is the amount of time that the output takes to be stabilized after power turn-on. In some devices, an enable pin is available to switch the oscillator output off and on.

Phase noise: Phase noise is a critical specification at very high frequencies and in applications requiring exceptional stability. This is the rapid short-term random variation in output frequency. Also called jitter, it produces a type of phase or frequency modulation. Measured in the frequency domain with a spectrum analyzer, phase noise is usually stated in terms of dBc/Hz.

A sine-wave output from an oscillator with no phase noise, called the carrier, would be shown as a single vertical straight line at the frequency of operation. The phase noise produces sidebands above and below the carrier. The amount of phase noise is expressed as the ratio of the sideband power amplitude (Ps) to the carrier power amplitude (Pc) in decibel form:

phase noise in dBc = 10 log (Ps/Pc)

Phase noise is measured at increments from the carrier of 10 kHz or 100 kHz, though other frequency increments down to 10 or 100 Hz are also used. The phase noise measurements are commonly normalized to a 1-Hz equivalent bandwidth. Typical phase noise values range from –80 to –160 dBc, depending on the frequency increment from the carrier.

Pullability: This is a measure of the amount of frequency variation that can be achieved by applying an external control voltage to a voltage-controlled crystal oscillator (VCXO). It represents the maximum deviation possible and is usually expressed in ppm. The control-voltage level is also given, and a linearity value in percent is sometimes provided. Typical dc control-voltage values fall in the 0- to 5-V range. The linearity of the frequency variation with the control voltage may be an issue.

5. Fox Electronics XO and VCXO SMD oscillators come in frequencies from 750 kHz to 1.35 GHz with stabilities to 20 ppm.

Packaging: There are many different types of crystal oscillator packages. In the past, metal can packages were the most common, but they've been overtaken by newer surface-mount (SMD) packages. Designated as HC-45, HC-49, HC-50, or HC-51, the metal packages commonly have standard DIP through-hole pins. A common SMD package size is 5 by 7 mm. The trend has been to make the packages thinner as demanded by cell-phone manufacturers.

COMMON OSCILLATOR CIRCUITS

Dozens of circuits have been developed for crystals. Most are variations of the common Colpitts, Pierce, and Clapp varieties. The circuit determines whether the crystal operates in its series or parallel mode.

In series-mode oscillators, one of the two logic inverters is biased into the linear region for amplification by R1 *(Fig. 3)*. C1 is a dc blocking capacitor. R2 sets the optimum crystal drive current. The crystal operates in the series mode. This type of oscillator isn't widely used because it's less stable than one that operates in the parallel mode.

For example, Pierce oscillators are commonly used inside embedded controllers *(Fig. 4)*. The crystal along with C1 and C2 are external to the processor. Again, R1 biases the inverter into the linear region. Capacitors C1 and C2 provide the necessary 180° phase shift along with the crystal.

The frequency of oscillation is higher than the series resonant frequency, but lower than the parallel resonance figure of the crystal. Capacitors C1 and C2 do affect the frequency of oscillation. The series combination of C1 and C2 plus the external stray capacitance (C_S) of the PCB in parallel with the crystal form what is called the load capacitance:

$$C_L = (C1C2)/(C1 + C2) + C_S$$

C1 and C2 are normally equal and fall in the 10- to 30-pF range. Stray capacitance is typically 2 to 5 pF. The crystal manufacturer will require you to specify this load capacitance for the desired frequency.

TYPES OF CRYSTAL OSCILLATORS

There are four basic types of packaged crystal oscillators: clock oscillators (XOs), voltage-controlled crystal oscillators (VCXOs), emperature-compensated crystal oscillators (TCXOs), and oven-controlled crystal oscillators (OCXOs).

The base XO is a crystal packaged with its oscillator. The frequency is usually fixed, but in some designs a trimmer capacitor may be provided to make adjustments for aging. XOs are for the least critical designs, usually as clock oscillators for processors or other digital chips. Typical accuracies range from 10 ppm to several hundred, with aging from ±1 to ±5 ppm/year *(Fig. 5)*.

TCXOs incorporate circuitry to compensate for the frequency variations that accompany temperature variations. This results in a far more precise and stable output frequency that's demanded by many applications. Cell phones and two-way radios are common examples.

The simplest form uses a thermistor temperature sensor in a circuit that operates a varactor (voltage variable capacitor) in a feedback circuit to keep the crystal frequency more constant. More elaborate schemes of compensation are also used.