Making oscillator selection crystal clear

Paul Rako - February 19, 2009

Oscillators are as ubiquitous—and, some might argue, as important—as power supplies in electronics systems, finding use in anything that needs a timing signal, from digital watches to TVs and PCs. Because of their important role in timing for electronics, their failure can bring down an entire system. For example, investigators in 1972 traced the cause of a train crash in Fremont, CA, to a faulty crystal oscillator on a control board. An inappropriate value for the oscillator’s tank capacitor overdrove the crystal, causing the part to jump into an overtone frequency. As a result, the train sped up rather than slowed down as it approached a station, and the resultant crash caused many injuries. Because of problems such as this one, many engineers have stopped using raw crystals to make their own oscillators. Instead, they buy off-the-shelf components whose packages contain the amplifiers, tank capacitors, and other parts.

All digital devices require clock sources, such as silicon and MEMS (microelectromechanical-system) oscillators, quartz crystals, or ceramic resonators. Telecommunications and servers, for example, might need a dozen clocks on a single PCB (printed-circuit board). Designers have implemented traditional clock sources with quartz-crystal resonators, but MEMS and pure-silicon resonators are gaining a foothold in this highly diverse market. In addition, less accurate resonators employ ceramic materials, such as lead-zirconium titanate. The application drives the suitability of a technology. For example, if you need a clock source with better than 1-ppb (part-per-billion) accuracy, you must abandon MEMS devices and instead use atomic-resonance devices, such as rubidium- or cesium-clock sources. These devices have 1-ppt (part-per-trillion) accuracy. A GPS (global-positioning-system) satellite, for example, needs this accuracy to maintain synchronicity with the rest of the system (Figure 1).

The humble ceramic resonator lies at the opposite end of the accuracy spectrum. You measure the accuracy of these devices as percentages because the parts-per-million measurement yields an unwieldy, large number. The typical initial accuracy of a ceramic resonator ranges from 0.5 to 0.1%, and drift due to aging or temperature changes can alter this range. As a result, an inexpensive ceramic oscillator can have a tolerance of only ±1.1%, whereas higher-end automotive and commercial products can have accuracies of ±0.25 and ±0.3%, respectively. These tighter-tolerance ceramic resonators target use in USB (universal-serial-bus) 2.0 circuits in commercial and automotive CAN (controller-area-network)-bus applications that operate at −40 to +125°C. Low-cost ceramic resonators, at frequencies of 200 kHz to almost 1 GHz, work well in embedded systems in which timing is not critical. Ceramic devices offer faster start-up and are often smaller than their quartz counterparts. They are also more tolerant of shock and vibration. Ceramic resonators are available from such manufacturers as Murata, Oscilient, AVX, TDK, and Panasonic.

For digital systems using UARTs (universal synchronous/asynchronous transceivers), you should do
an error-budget analysis to ensure that the baud rate you derive from the resonator frequency stays in spec. If you use the UART only during code development, you might be able to switch in a ceramic resonator in production and save money.

Note that some silicon oscillators use RC (resistance/capacitance) or LC (inductance/capacitance) tanks and no ceramic or quartz. These oscillators also have a broad range of accuracy commensurate with their price. Companies such as STMicrosystems manufacture oscillators that have all the advantages of ceramic resonators and can be even smaller and less expensive. “The main point regarding silicon oscillators is their robustness versus the fragility of a crystal,” says Louis Grantham, product-marketing engineer at the company. “Plus, the manufacturability of crystals is more difficult than that of ICs.”

It began with Quartz

A crystal oscillator uses the mechanical resonance of a vibrating crystal of piezoelectric material to create an electrical signal with a precise frequency. This frequency commonly keeps track of time, as in quartz wrist watches; provides a stable clock signal for digital integrated circuits; and stabilizes frequencies for radio transmitters and receivers. Engineers have been using these crystals to establish radio frequencies since the 1920s when AM Nicholson at Bell Telephone Laboratories and Professor WG Cady of Wesleyan University, working with Rochelle salt as the crystal, observed the reaction of a resonant piezoid on a driving circuit (Reference 1). However, researchers did not develop methods for high-volume manufacturing until World War II (Reference 2). If you cut the resonator elements in a quartz crystal at the correct angle in relation to the crystal matrix, you can eliminate effects due to temperature. Some cut crystals have a zero temperature coefficient, whereas the LC cut finds use as a thermometer (Figure 2).

Just because you can make a quartz crystal from a mineral, do not assume that a crystal oscillator is a low-tech device (Reference 3). Manufacturers of today’s quartz crystals grow the crystals in large reactor ovens, or autoclaves, at high temperatures and pressures of 30,000 psi (pounds per square inch) or more (Reference 4 and Figure 3). It can take months to grow the quartz crystals in an autoclave, and any seismic activity or the slightest degradation or loss of electric power to the heaters would ruin the entire lot. For that reason, NDK, a Japanese company that has made crystals for decades, now has autoclaves in Belvidere, IL. The company based its decision to locate its newest facilities in the Midwest on the reliability of the region’s electric-power grid and low incidence of earthquakes.

“We put mined quartz into a huge vessel that we adapted from battleship-cannon technology,” says Craig Taylor, general manager of business and applications development at the company. “We then put seed quartz in baskets above the mined quartz. By adding [a sodium-carbonate or sodium-hydroxide] electrolyte and applying great pressure and temperature, all the natural quartz dissolves and migrates upward. It attaches itself to the seed quartz, and all the dirt and impurities are left in the bottom of the vessel.”

Amplification and buffering turn a crystal into an XO (crystal oscillator). Adding temperature-compensation circuitry yields a TCXO (temperature-controlled crystal oscillator) with accuracy of 1 ppm (part per million), and putting the entire oscillator into a temperature-controlled-oven package yields an OCXO (oven-controlled crystal oscillator) with accuracy in the part-per-billion range. A 30-MHz oscillator with 1-ppm accuracy will have an error of only 30 Hz over time and temperature. Only rubidium and cesium-atomic standards are more accurate, in no small part because atomic resonance is independent of temperature. Some companies are also offering PXCOs (programmable crystal oscillators), which allow you to write to digital registers in the chip to adjust the frequency.
Adding a PLL (phase-lock loop) to a crystal allows it to emit a higher frequency at lower cost than a quartz crystal, according to Nancy Zhang, product-marketing manager at Pericom. According to Kay Annamalai, senior marketing director at the company, a third-overtone crystal allows frequency of only 150 MHz. For needs beyond that frequency, designers often add a PLL. He describes a proprietary Pericom technique that multiplies the frequency without using a PLL. This method offers the same reduction in crystal cost but also improves jitter performance. The company’s XP technology avoids the use of a PLL but allows frequencies greater than 150 MHz.

A PLL can also improve performance, according to CS Lam, a director at Epson Electronics America. Lam notes that the company has achieved less-than-10-ppm accuracy using fractional-PLL circuitry. He also points out that the first PLL-based crystal oscillator with less than 1-psec-rms phase jitter at 12 kHz to 20 MHz appeared in 2004 (Reference 5).

Adding a PLL also allows you to electronically vary the frequency of operation to help comply with FCC (Federal Communications Commission) and CE (Conformité Européenne) radiation standards. When the PLL varies the clock frequency, the high-amplitude spike of EMR (electromagnetic radiation) or EMI (electromagnetic interference) spreads the radiation over a frequency band. Note that this technique does not reduce the amount of radiation; it just sweeps over a band such that the energy-measurement instruments give a lower reading. The EMI leaves the measuring bandwidth of the spectrum analyzer, lowering the measurement readings and helping your product pass the test for compliance.

Spread-spectrum clocking also plays a role in oscillator selection. It has two broad applications: power supplies and system clocks in computers and telecommunications. Power supplies can use oscillators that vary by as much as 10%, spreading the energy over a wide band and dramatically reducing the measurement results. These devices, which employ ring oscillators or LC tanks, do not require quartzlike accuracy. The PLL portion of the oscillator circuitry uses the output of the silicon oscillator to create a spread-spectrum clock. Just as with other pure-silicon oscillators, the parts are more resistant to shock and have faster start-up. Because an LC tank or a ring oscillator has a much lower Q (quality) factor than any quartz crystal or MEMS resonator, you might expect the silicon oscillator to take more energy to keep going. However, it takes only microwatts to maintain the oscillation because the power consumption in oscillators depends on the process and architecture of the PLL and temperature-compensation circuitry.

The other application of spread-spectrum clocking is digital systems that have only a few percentage points of dither, or noise. They must maintain tight timing, but even a small amount of spread-spectrum clocking can allow a system board to pass FCC testing. Pericom’s Annamalai notes that the spread-spectrum clocking works especially well in memory subsystems. “Memories tend to be high-speed, so you want to spread that single spectrum,” he says. The company uses the Hershey’s Kiss spreading profile, which takes its name from the popular candy, whose shape it mimics.

Lexmark discovered and patented this profile. To understand this response, imagine that a sinusoidal frequency is modulating the operating frequency of the system clock; the average time that the oscillator spends at the end frequencies will be greater than the time it spends between the ends. In other words, the clock lingers at the outside bounds of the frequency excursion, where the sinusoidal modulation is slowly changing direction. This change gives rise to the “bat-ears” frequency-domain profile (Figure 4). By using the Hershey’s Kiss waveform, manufacturers can eliminate bat ears and allow your system to pass FCC testing.

Pericom uses quartz, a high-Q source with low jitter for system clocking. By melding this crystal with a high-performance, low-jitter PLL, the company provides a swept-spectrum oscillator that consumes minimal power and combines the benefits of both quartz and silicon.
Power consumption is another factor to consider when selecting an oscillator. Start-up Mobius Microsystems offers a pure-silicon oscillator that provides near-quartz accuracy, fast start-up, and high shock resistance. However, the company achieves these features by running the silicon tank at a high frequency and then dividing the frequency down, resulting in higher power consumption than that of quartz-based devices. Silicon-process and -design techniques are improving quickly, though, so silicon oscillators should rapidly improve in almost every specification.

Another company making advances in silicon technology, Silicon Laboratories, makes both pure-silicon oscillators and devices that adapt a PLL to a quartz crystal (Reference 6). These parts offer accuracy matching that of low-end crystal oscillators. “The Holy Grail is to eliminate the [need for a] mechanical resonator,” says Mike Petrowski, director of marketing for timing products at the company. “If you eliminate that mechanical resonator, you improve reliability, simplify your manufacturing flow, and [make the device] easier to mass-produce.” Petrowski maintains that silicon oscillators do not consume excess power because they achieve their accuracy with temperature compensation, not a PLL that divides down a higher frequency.

Note that silicon oscillator can mean a lot of things—from a cheap part that replaces a ceramic resonator to a device with quality matching that of quartz. Always evaluate the power consumption to ensure that the technology you use is appropriate for your application. Be aware of subtleties, such as the fact that a quartz crystal or a MEMS oscillator draws more current for the several milliseconds that it takes to start up. This excess current draw may present a problem in micropower applications or in applications that require the part to continually start and stop.

Besides accuracy and power, another key spec in oscillators is jitter, or phase noise, the cycle-b-cycle change in frequency. For example, a stable device could alternate operation at 1 MHz during one cycle with operation at 2 MHz during the next cycle, providing an average frequency of 1.5 MHz. However, this huge change in cyclic frequency would make the part useless in most applications; a switching power supply could not work over such a broad range, and a PLL would have difficulty locking into such a high-jitter source. Any system using such an oscillator could not include ADCs or DACs because the variance in frequency would ruin the digital processing, even though the average frequency is stable. For this reason, the oscillator-design groups in many companies are in the analog sections of the company. A PLL is an analog component, and many of the specs, such as jitter, are important in analog circuitry.

Although jitter and phase noise are the time- and frequency-domain representations, respectively, of the same condition, it is easy to misrepresent jitter specs, according to Doug LaPorte, design-section leader for signal-conditioning products at Linear Technology. Some companies spec jitter only over a certain frequency range, he says. These companies may produce phase-noise plots that integrate only a certain amount of that phase noise and omit other bits of the noise. Optical-communications standards, such as SONET (synchronous-optical networking), transmit, perform PLL, and then retransmit. The loop has a design bandwidth that allows the system to reject phase noise outside the loop but allow noise inside the loop. “[These manufacturers] get away with a spec of, say, 20 kHz to 10 MHz,” LaPorte notes. “Beyond that [limit], they don’t care.”
amount of R&D and patents rolled into these parts, and it is absolutely possible to make a low-jitter PLL, especially with finer IC geometries.”

The nature of a PLL, with its analog filtering, phase detection, and VCO (voltage-controlled oscillator), gives rise to increased jitter at all points of the circuit. During the last five years, designers began to use bond wires as small inductors on ICs or to place discrete spiral inductors on IC die. Now that IC designers can use inductance as well as capacitance as reactive elements, the filters and tank circuits can all have higher Q and more poles and zeros. Maxim Integrated Products, for example, uses LC-based oscillators rather than ring oscillators in its designs. “Ring oscillators tend to have more jitter than an LC type,” says Paul Nunn, business manager for precision oscillators at the company. Such companies as Pericom, Silicon Labs, SiTime, On Semiconductor, and Fox Electronics use these high-quality PLLs because they allow oscillators to have adjustable frequency and low jitter.

MEMS devices add a twist

MEMS oscillators share the amplifier and perhaps the PLLs of quartz oscillators but use a small, vibrating silicon mass rather than a quartz crystal. This approach offers better MTBF (mean time between failures), shock resistance, and reliability. For example, JEDEC (Joint Electron Device Engineering Council) and HTOL (high-temperature-operating-life) testing of silicon yields a 500 million-hour MTBF, whereas quartz yields only a 10 million- to 30 million-hour figure, according to Piyush Sevalia, vice president of marketing at SiTime. And, whereas a 1-kHz vibration readily shows up in the jitter performance of a quartz oscillator, neither MEMS nor silicon oscillators are sensitive to this vibration. MEMS devices resonate at a fundamental frequency in a mode that incident vibration does not modulate. However, MEMS and quartz oscillators have slower start-ups than those of pure-silicon oscillators.

One challenge in manufacturing MEMS oscillators is keeping the vibrating silicon element atomically clean. Even a monomolecular layer of atoms on the vibrating beam can cause the part to go out of spec, and manufacturers use various methods to overcome this challenge. For example, Discera uses “getters,” reactive materials for removing traces of gas to absorb any incidental gases or material over the life of a part. SiTime, on the other hand, uses a technology that Bosch first developed (Reference 4).

Rather than place a glass or epoxy cap over the MEMS element, SiTime creates the silicon beam in a matrix of glass, caps that matrix with polysilicon, and then dissolves the glass with hydrofluoric acid. The company then seals off the beam with a thicker layer of polysilicon. All this work occurs in an epitaxial reactor, a high-vacuum semiconductor machine that offers one of the cleanest environments on earth. This exotic processing allows SiTime to sell oscillators with quality that rivals that of quartz oscillators. The company’s products incorporate both a MEMS-resonator die and a CMOS die into one package that can be smaller and thinner than a quartz oscillator (Figure 5).

Both Discera and SiTime oscillators are fully programmable because they integrate PLLs. Discera also offers a less-than-$500 kit that includes a handheld programmer and 200 parts; the programmer connects to the USB port of your computer. According to Gerry Beemiller, vice president of sales and marketing at Discera, the kit allows you to build a highly accurate oscillator with 1- to 150-MHz frequency. In contrast, SiTime touts fast turnaround rather than in-field programmability. Because it employs no quartz processing, the company claims that it can—within days—provide you a part that operates at any frequency.

Accurate time is always critical in a sampled-data digital system. If the somewhat-shabby timebase
of a ceramic resonator or low-performance silicon oscillator doesn’t fit your needs, you can choose a part from the entire spectrum of quartz technology. Add those choices to the higher-performance silicon oscillators from Silicon Labs and the MEMS oscillators from SiTime and Discera, and you can see that choosing an oscillator is crucial. Understand all the trade-offs involving accuracy, power consumption, jitter, and programmability, as well as any spread-spectrum requirements. And remember that it is always desirable to at least provide for a spread-spectrum oscillator on your power supply or system clock in case you fail FCC testing. This scenario always occurs at the worst possible time: just when you are ready to ship your product; having a sophisticated oscillator that you can substitute for the fixed one is always good insurance. After weighing all these factors and how they match the needs of your application, choosing an oscillator should become crystal clear.

References

4. Conner, Margery, “Crystal grinding: when electronics were really hands-on,” EDN, April 4, 2008.