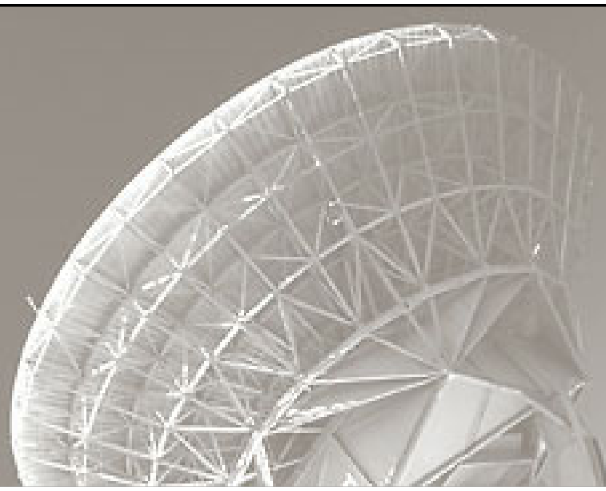
The Design and Performance of Precision Miniature TCXOs

APP NOTE



GREENRAY

Ever since the advent of the use of quartz crystals as frequency control devices, there has been an ongoing quest to improve their temperature stability. After a brief review of the history of crystal oscillator temperature compensation, this article will describe the current state-of-the-art in TCXO temperature compensation technology and the associated crystal resonators.

When the first crystal oscillators were built in the 1920s, the only crystals available, such as the X-cut, exhibited poor temperature performance. The development of the AT-cut crystal was a major step toward making temperature compensation feasible[1]. The AT-cut provided for a relatively flat frequency vs. temperature curve centered on +25 °C. Until about the mid-1940s, the aging and temperature characteristics of crystals were not good enough to make precision corrections practical[2]. Leaky packages led to poor aging drift and deficiencies in crystal plate and wafer design produced crystals with severe activity dips and coupled modes[3]. This produced significant frequency perturbations that limited the effectiveness of any attempt at compensation. But advances in quartz plate design and crystal packages such as the cold weld holders made it possible to produce crystals with relatively smooth frequency vs. temperature curves and aging rates as low as 1×10^{-9} (or 1×10^{-3} ppm) per day.

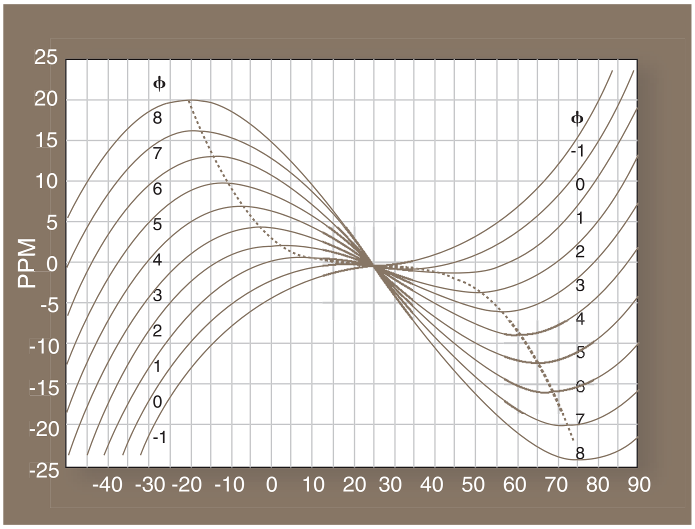


Figure 1. Family of characteristic temperature curves for fundamental frequency of AT-cut crystal.

Thermistor/resistor Network Compensation

Thermistor/resistor TCXOs have been the mainstay of crystal oscillator temperature compensation for 50 years. A correction voltage generated by a network of one or more thermistors cancels the frequency vs. temperature variation of a voltage-controlled crystal oscillator. The introduction of voltage-variable capacitance varactor diodes along with improvements in negative-temperature coefficient thermistors made it possible to compensate crystals to a greater precision[4]. As early as 1961, compensation ratios of greater than 100-to-1 were being achieved. This would indicate that a crystal with a peak-to-peak deviation of 40 ppm over temperature could be compensated to a level of 0.4 ppm. Today, ratios of two orders of magnitude are about the limit for thermistor/resistor compensation, although achieving that level is facilitated by improved, automated systems and computer analysis power. But even today, achieving stabilities of better than 0.5 ppm requires multiple temperature runs and repeated network adjustments with at least three thermistors. Some attempts at automation of the compensation process using resistor trimming or digital adjustment of thermistor sensitivities have been moderately successful[5], but these configurations could not be easily integrated for small package size requirements.

Digital Temperature Compensation

By the late 1970s, advances in integrated circuit technology made it practical to realize compensation systems employing analog-to-digital conversions and solid-state memory[6]. Although the implementations were crude by today's standards, digital TCXO's achieving better than 0.1 ppm performance were produced by several companies, including Rockwell Collins and Greenray Industries. Other digital implementations have been developed over the years, many with embedded computing power to facilitate calibration and system operation. Some employed elaborate temperature measurement schemes such as dual-mode crystal self-temp sensing. Although some of these designs achieved temperature stabilities of 0.05 ppm or better, they were larger and relatively complex assemblies, often with spurious noise generation problems.

Analog Integration

As the capabilities of large-scale integration continued to expand, it became possible to include more of the functions required for temperature compensation into a single IC. This has led to the current generation of ASICs that allows the construction of a precision analog TCXO with only two components: the ASIC plus the quartz crystal.

The latest devices that have emerged for TCXO applications are complex, large-scale ICs combining precision analog functions, non-volatile digital storage, varactor diodes and RF oscillator circuitry[7]. Figure 2 (see Page 3) illustrates a block diagram of a generic device. Although the first-generation fabrications resulted in relatively large die, reductions in geometries have produced smaller ICs that enable a complete precision TCXO to be housed in a package as small as 3.2 mm x 5 mm.

Polynomial function generator

The heart of the ASIC is the polynomial function generator engine. The goal is to produce a temperature-varying voltage that will match the VCXO voltage required to keep the oscillator frequency exactly on nominal over the full temperature range. Starting with a linear temperature sensor and then using a series of analog multiplications, the coefficients of a high-order polynomial are simulated. This function is described as:

$$\Delta f/f(T)= a_0+a_1(T-Ti)+a_2(T-Ti)^2+a_3(T-Ti)^3+a_4(T-Ti)^4+a_5(T-Ti)^5$$

Where a_0 to a5 are the coefficients of the polynomial to be generated, T is the current temperature and Ti is the inflection temperature of the crystal (the temperature where the crystal curve is centered with respect to the lower and upper turning points, usually around +26 °C).

The range of adjustment of the variables is calibrated to cover the AT-cut crystal angles over temperature. All temperatures are referenced to the crystal inflection temperature. The coefficient values are stored as digital numbers in non-volatile registers on the chip. Although the ideal AT crystal should follow a third-order curve, non-linearities in the circuitry and the crystal require that higher-order terms be included in order to obtain a match to the required compensation voltage curve. The crystal inflection temperature is important in matching the curve and is one of the variables that must be programmable in order to use a wider range of crystals. Some miniature strip crystals may have inflections as high as 40 °C, which can make accurate curve fitting difficult.

Integrated oscillator functions

In addition to the function generator, all other oscillator functions are included on the latest chips. A precision low dropout (LDO) voltage regulator supplies power to all of the on-chip circuitry. Because of the stable voltages that must be maintained to achieve the frequency stability required, a precise reference voltage source is essential. Operation as low as +2.7 Vdc is possible.

The crystal oscillator drive circuitry is on-chip with programmable crystal drive current to accommodate a range of crystal impedances and frequencies. The voltage variable capacitors that adjust the oscillator frequency are usually implemented as a MOS structure instead of a conventional doped junction diode. A relatively high tuning sensitivity is required due to the low-voltage operation of the devices and may exceed 50 ppm/V.

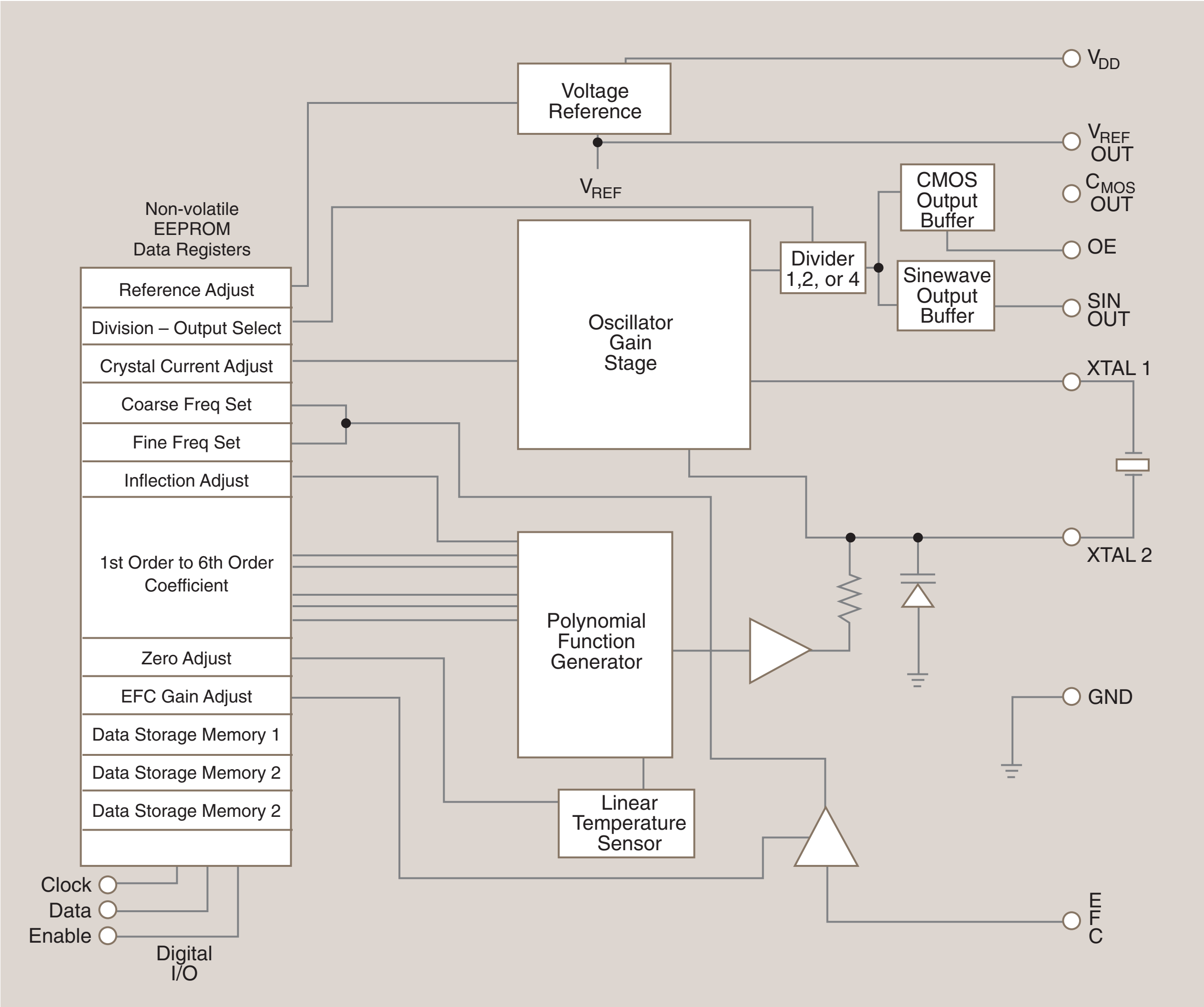


Figure 2. Integrated TCXO ASIC.

Output conditioning circuitry buffers the crystal and oscillator from the load and provides the proper output voltage levels. Most ASICs can supply either a CMOS squarewave or a lower-power 1 Vpk-pk clipped sinewave. Electronic frequency control for implementing a VCXO function is available. A few bytes of undedicated user memory are useful for storing serial numbers and other characterization data for improved automation.

Precision AT crystals

As has been the case, it is impossible to produce a precision TCXO without a high-quality crystal. While good crystals are still produced as round blanks in conventional two-leaded welded packages, their size precludes their use in many miniature oscillator designs. This has led to the development of AT strip crystal designs with excellent performance in small form factors. Although the motional capacitance is lower, it is possible to achieve sufficient tuning sensitivity for compensation. With proper blank design, packaging and careful processing, performance equivalent to or, in some cases, even better than conventional round crystals is achieved. Aging rates can be low, achieving a fraction of a ppm per year.

Calibration and Compensation Procedures

Due to the nature of the crystal/oscillator combination, it is necessary to measure and calibrate each oscillator individually when considering sub-ppm levels. Although most TCXOs in a given batch are similar, no two are the same when attempting to match curves to less than a part per million. It is important to actively characterize each unit over the temperature range of interest in order to calculate the initial coefficient parameters that will be loaded into the unit.

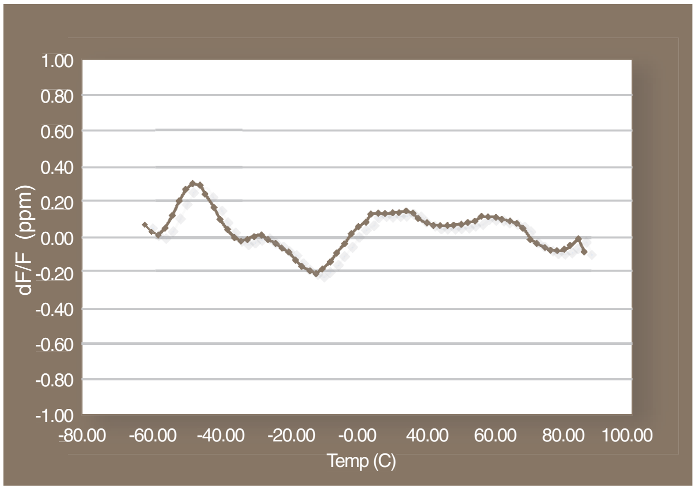


Figure 3. Frequency vs. temperature of 20MHz TCXO at 2°C intervals.

A requirement run is performed where each oscillator is operated over the temperature range of interest while determining the VCXO control voltage that is necessary to keep the output on nominal frequency. This data is then input to a curve-fitting algorithm that calculates the polynomial coefficients that give the best match. These coefficient values are loaded into the ASIC and another temperature test is performed to determine if the frequency drift is within the specification allowance. While some yield may be obtained on the first run depending on the specification, most units will require a correction to be made and then re-verified. This is due to the accuracy and repeatability of the initial measurements.

With programmable ASICs, automated test systems are set up to perform all of these functions without operator interaction.

Static frequency vs. temperature characterization

The achievable frequency vs. temperature performance is a function of how closely the compensating voltage curve generated by the polynomial generator matches the required voltage of the VCXO. Many variables affect this capability, including the tuning linearity of the VCXO; the quality of the crystal, i.e,. how closely it follow the ideal AT curve; the temperature coefficient of other oscillator components; the inflection temperature of the crystal; and the stability of the voltage reference. Figure 3 shows the frequency vs. temperature performance that can be achieved.

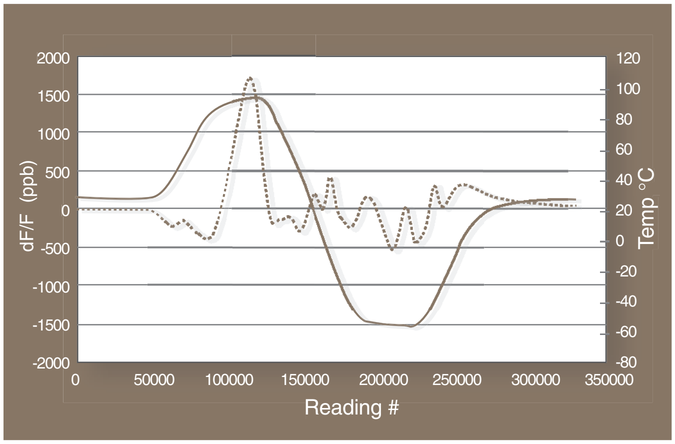


Figure 4. 20MHz TCXO frequency during a °C/minute temperature ramp.

Temperature ramp testing

The frequency excursions that occur during changing temperature conditions will vary depending on the direction and rate of the temperature change. An important feature is close thermal coupling between the crystal and the temperature sensor of the ASIC. This thermal path is inherently short with a miniature package since the crystal and ASIC are physically close. Because of this, most small TCXOs will perform well. Figure 4 shows a 20 MHz oscillator during a slewing temperature run. The red curve shows the chamber temperature on the right y-axis, and the blue curve is the oscillator frequency on the left y-axis. The x-axis plots time as normalized to the reading number (each reading takes 20 ms). Starting at +25 °C, the chamber is ramped up to +90 °C at a rate of 8 °C/minute. After stabilizing, it is ramped down to –60 °C at the same rate. Except for the peak at the hot end where the temperature exceeded the compensated range, it can be seen that the effect of the ramp is minimal, with little hysteresis evident from ramping in opposite directions.

Perturbations and micro-jumps

TCXO crystals have historically been plagued with anomalies in their temperature performance caused by blank design or imperfections in the processing and manufacture of the crystal. Marginal blank geometry can lead to coupling of other modes of oscillation that may be close to the frequency of the desired mode. These modes can interfere with the oscillator frequency at various temperatures causing increases in the crystal resistance or "activity dips" and resulting frequency excursions. These perturbations typically occur over a narrow temperature band. It is possible that the circuit may cease to oscillate at these points, or may not start when power is applied.

Micro-jumps

Another inconsistency that may occur over temperature is a jump or step offset in frequency. These offsets are small and often are not observed under normal TCXO testing. Many times, TCXOs are only tested at six or eight points over the temperature range. Under these conditions, many perturbations and jumps will go undetected. In applications where this type of irregularity is critical to system performance, the oscillators should be tested over many more points. Testing at 28 intervals is a good compromise that will catch most perturbations without a great increase in test time.

For the greatest confidence, the frequency of each oscillator should be continuously monitored as the temperature is ramped from one extreme to the other and back. This type of test guarantees that any perturbation or micro-jump that is present will be captured. Figure 5 shows the screening results of a 20 MHz TCXO that was monitored during the 8 °C/minute ramp profile. For this entire time, the output frequency is continuously recorded 50 times per second with no dead time between the readings. The blue line is a plot of the difference between successive readings, which highlights any instantaneous jumps. This AT-strip crystal shows no perturbations and just a few small micro-jumps throughout the test, which indicates a TCXO with exceptional performance.

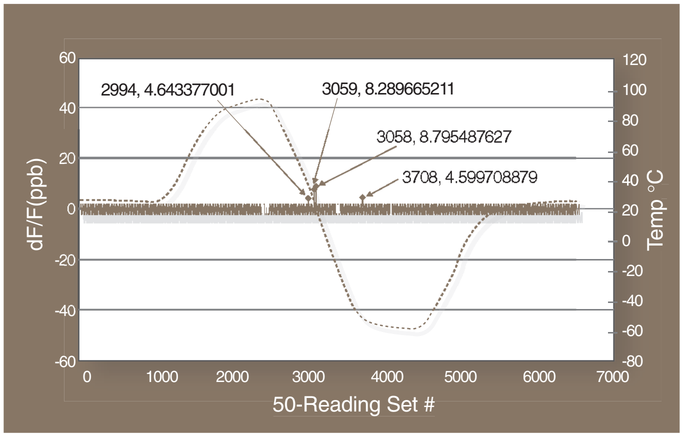


Figure 5. First difference between successive continuous frequency samples.

Figure 6 has zoomed in on the area around reading No. 3059. The y-axis is the frequency in Hertz indicating a step of around 10 ppb. These small steps are fairly repeatable, although they may not appear when the temperature is slewed in the opposite direction.

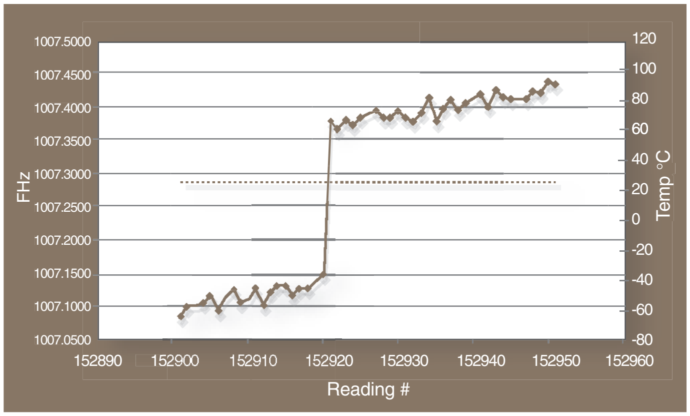


Figure 6. Expanded view of 10 ppb micro-jump.

Aging

One other parameter of concern to most TCXO users is the long-term drift of the frequency caused by aging. Although other oscillator components can contribute to aging, in a well-designed oscillator the aging is primarily due to the crystal. Changes in the crystal's resonant frequency arise because of mass transfer to or from the quartz blank. Relaxation of mounting stresses can also play a role. Advances in crystal design and processing have reduced the aging capability to under 1 ppm per year, even for miniature packages. Long-term projections for the 10- or 20-year expected life of an oscillator can be less than 5 ppm, as the aging rate decays with time. Aging effects can be projected with curve-fit extrapolation using the MIL-SPEC logarithmic model:

$$\Delta f/f\ (t) = a_0 + a_1 \ln(1+a_2 t)$$

Where t is the time in days, and a_0, a_1 and a_2 are numerical coefficients adjusted for curve fitting to the sample data.

Acceleration sensitivity

If the oscillator's operating environment includes vibration and shock levels, the acceleration or "g" sensitivity (where $g = 9.8\ m/s^2$) of the crystal can be an important parameter. Vibration levels will modulate the output causing noise sidebands on the signal. Shock pulses will produce short perturbations in the frequency, which may be problematic for phase locked loops or similar circuitry. The miniature AT strip crystals may be designed to provide low sensitivity to these forces. Levels below 5×10^{-10} (or 5×10^{-4} ppm) per g in the worst axis are routinely produced for critical applications. Because of the design of the strip resonator and its mount, the worst axis for acceleration is predictable. The vector always points in the vertical or z-axis, almost directly perpendicular to the crystal plate. The sensitivity in the x and y axes is extremely low. These crystals can also withstand high levels of pyrotechnic shock. Some have been tested to 100,000 g.[8]

Future trends

Since the basic TCXO architecture has been integrated into a single IC, which is suitable for many applications, further reductions in the size of precision oscillators will require smaller resonators. Although bulk-mode quartz resonators can be made small, physical limitations preclude making usable devices below a certain size. Surface-mount packages with 3.2 mm x 5 mm or smaller footprints (Figure 7) are available with reasonable motional parameters and stabilities. But reductions much beyond this level may require advancement of resonator technologies. Silicon micro-machined resonators can be fabricated on the same die as the oscillator circuitry[9]. Although these oscillators have not achieved the stability of a precision TCXO, further improvements are directed toward this goal. These devices may soon begin to displace quartz oscillators in lower-end, high-volume applications, but quartz crystals will still be required for precision frequency control for the foreseeable future.

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