CRYSTALS AND OSCILLATORS

By Jerry A. Lichter

Frequency control devices are generally piezoelectric devices, electromechanical in nature. Mechanical considerations (such as vibration, shock, and handling) of these devices are as important as electrical considerations. Frequency control is required in varied applications from microprocessor timing to radio station transmission.

Frequency control devices such as quartz crystals and oscillators are quite fragile. These devices should be handled much more carefully than most other components used in the electronic industry, even though the packaging looks very rugged.

Resonators and filters are usually discrete piezoelectric devices. Oscillators incorporate a resonator along with an active device and several discrete components to produce a stand-alone frequency control device.

RESONATORS AND FILTERS

Resonators and filters use the piezoelectric properties of various materials. The word piezoelectricity means "pressure-electricity". Thus, those devices are electromechanical in nature. Some of the materials which could be used are Rochelle salt, Tourmaline, ceramic, and silicon dioxide. Of these, ceramic and silicon dioxide (quartz) are used almost exclusively.

Theory of Operation

Monolithic quartz crystals are generally used for two pole filters. These devices are typically "AT" cut and the theory of operation is similar to resonators except that the characteristics are highly dependent on the electrode configuration.

Quartz crystal resonators and crystals used in discrete crystal filters have an equivalent circuit as shown in figure 1.
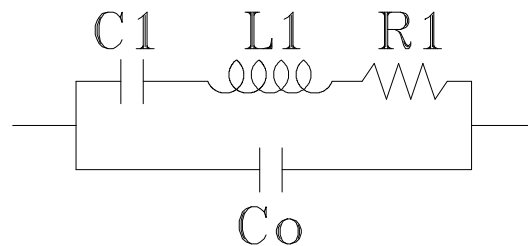

Figure 1

The motional capacitance C1 and motional inductance L1 define the series resonance of the device by the equation $fs=1/(2\eth((L1*C1)^{1/2}))$. This is the point when the magnitude of the motional capacitance impedance equals the motional inductance impedance and thus they cancel out. In many cases the series resonance point can be approximated by finding the point of minimum impedance (this series resonant point is also near the zero phase shift point) and this minimum impedance will be approximately the motional resistance(R1) for these cases.

Series resonance crystals are generally used in crystal filters and resonator circuits which require no phase shift from the crystal in order to oscillate. The effective resistance of the crystal in this type of oscillator circuit is approximately equal to the motional resistance R1. The frequency of operation in this case is the series resonant frequency of the crystal.

The shunt capacitance Co (the sum of electrode capacitance Ce and holder capacitance Ch) becomes important in working with frequencies above series resonance.

In this region the motional inductance impedance increases and the motional capacitance impedance decreases, resulting in a dominant inductive impedance. When the motional inductance impedance equals the shunt capacitance impedance the anti-resonant point is realized. Crystals intended to operate between series resonance and the anti-resonant point are called "parallel resonant crystals". These crystals are specified by the load capacitance (CL) that they are intended to work into. The equivalent series resistance (the equivalent resistance at the load capacitance specified) of a parallel resonant crystal can be calculated by $ESR=R1*((1+Co/CL)^2)$. The shift in frequency from series to the parallel resonant point is given by $\Delta f=(C1/2)*(1/(CL+Co))$. $\Delta f*10^6$ would give the answer in ppm. The shift in frequency from one parallel resonant point to another is given by $\Delta f=(C1/2)*((CL2-CL1)/((CL2+Co)*(CL1+Co)))$. Again $\Delta f*10^6$ would give the answer in ppm. Also note in all the above equations that all capacitances must be in the same units (ie pf). Although it is possible to operate a crystal intended for one application in another, it is important to note the calibration will now be off by the original calibration plus the shift per the above calculation. Also, the temperature drift varies from one CL to another and thus is no longer optimized for the applications. For this reason the idea of a universal crystal for multiple applications is not advisable.

Ceramic resonators are similar to quartz resonators with an addition of a shunt resistance Ro due to a high resistance path through the ceramic resonator. Other resonators, by the definition of a resonator, will be similar in nature to the above resonators. The resonant point will be set by the equivalent inductive/capacitive resonance.

Characteristics

Many different cuts of quartz (different angles of cut from a reference) have been developed for commercial use. AT, BT, and SC cuts are all a thickness shear mode of vibration (see figure 2).
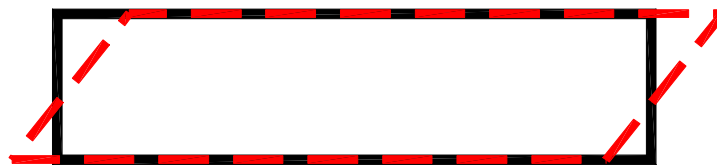

FIGURE 2

Thus, these cuts generally cut into round thin disks with the thickness inversely proportional to the frequency. These disks, or blanks, have electrodes placed on each side which are used to make the electrical connection to the crystal. The lowest frequency response is the fundamental mode of the crystal. There are also responses at approximately three times this fundamental frequency, five times, seven times, etc. Those are the third overtone, fifth overtone, seventh overtone, etc.

The AT cut is the most commonly used of these "high frequency" cuts. It is estimated that over 90% of quartz crystals produced today are AT cuts. The AT cut temperature coefficient is a cubic curve (see figure 3).
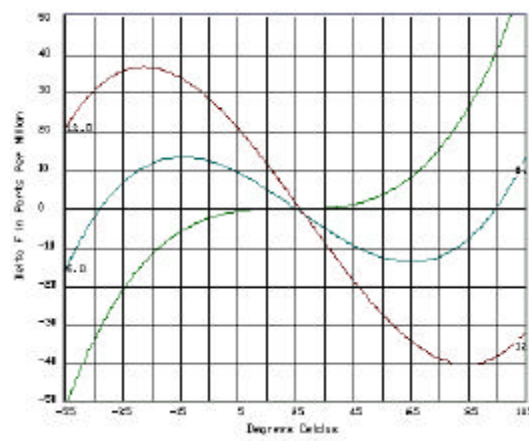

FIGURE 3

The specific shape of the curve and turnover points can be adjusted by small changes in the cut angle. This temperature characteristic gives this cut of crystal versatility for a wide range of applications and temperature ranges. The frequency constant is 1.661 MHz-mm, and is generally limited to approximately 40 MHz on the fundamental mode for small diameter blanks. Using contouring techniques the low end of the AT frequency range is approximately 500 kHz, but is dependent on holder size. Spurious or unwanted responses in the AT cut are typically predictable and can be controlled well using energy trapping techniques. However, spurious margins may need to be traded off with such parameters as pullability (the amount the frequency changes with load capacitance changes).

The BT cut, having a frequency constant of 2.536 MHz-mm, can extend the upper frequency range above that of the AT cut to more than 50 MHz. The BT cut is not as widely accepted as the AT cut because of its poorer temperature characteristics in most applications. The temperature curve is a downward parabolic curve.   The turnover point can be varied with the cut angle and the curve formula is generally $f=-0.040*(To-Ta)^2$ where To is the turnover temperature (°C), Ta is the temperature of interest (°C), and f is in ppm.

The SC (stress compensated) cut is similar in design to the AT cut except it is a doubly rotated cut. This means that the angle it is cut out of the quartz bar is rotated about two axis instead of just one from the three reference axis. The frequency constant for the SC cut is 1.797 MHz-mm. Coupled modes are generally worse than the AT cut and crystal resistance is generally higher. Much more care must be used in converting designs from one overtone of operation to another. With proper design considerations the SC cut yields a usable crystal with a very small frequency variation with temperature (approximately +/- one ppm over a ±25 °C. range).

The CT and DT cuts of quartz crystals are both a face shear mode of vibration (see figure 4).
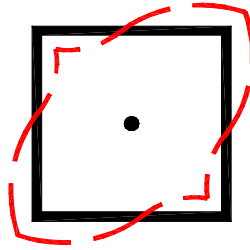

FIGURE 4

These two cuts have similar characteristics. The CT cut can generally be designed for frequencies within 300 kHz to 900 kHz and the DT cut from 75 kHz to 800 kHz. Both cuts have a downward parabolic frequency vs. temperature curve. The DT is generally preferred where the frequency allows either because of its lower temperature coefficient (approximately -0.060ppm/$^\circ$C². for the CT and -0.018ppm/$^\circ$C². for the DT). The GT cut of quartz crystal is a width-extensional mode of vibration. The GT cut can be designed for frequencies from approximately 100 kHz to 3.0MHz. The temperature coefficient is very nearly zero over the temperature range from -25°C. to +75° C. A temperature variation of ±15°C. on either side of the midpoint of this flat region will not change the frequency more than 0.1 ppm. The E (or 5 deg. x cut) and the MT cuts of quartz crystals are both a longitudinal mode of vibration (see figure 5).
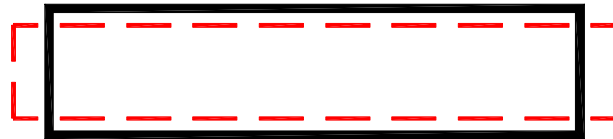

FIGURE 5

The E cut can generally be designed in the 50 kHz to 250 kHz range. The E cut is widely used for low frequency crystal filters because it has a low Co/C1 ratio and reasonable low temperature coefficient. In most cases the turnover temperature can be varied from approximately 0 $^\circ$C. to 50 $^\circ$C. The MT cut can usually be designed in the 80 kHz to 200 kHz range. The temperature coefficient for the E cut is approximately -0.040ppm/$^\circ$C² and -0.038ppm/$^\circ$C² for the MT cut.

The H, J, NT, and XY cuts are all flexure modes of vibration. The H, XY, and NT cuts are length-width flexure (see figure 6).
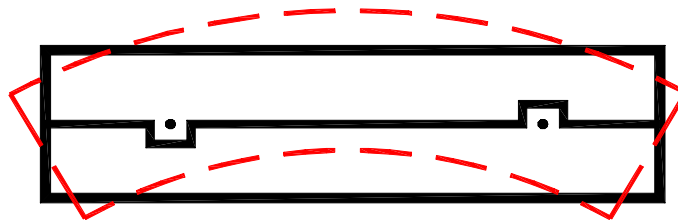

FIGURE 6

4

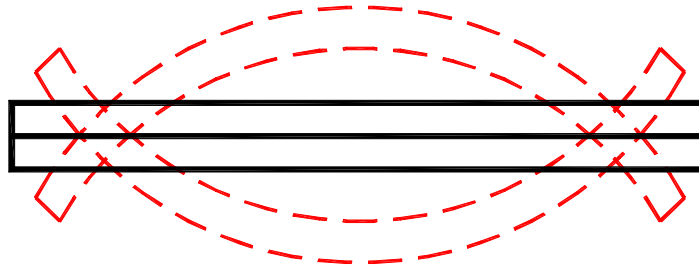The J cut is a length-thickness flexure (see figure 7).

FIGURE 7

The J plate (cut) has the lowest frequency range (1 kHz to 12 kHz) of these low frequency crystals. The J plate is actually two quartz plates bonded together. The two plates are selected so that one plate's mechanical motion is out of phase from the other for a given electrical field applied. This produces very low frequencies. The H plate (cut) can be designed within a frequency range of approximately 8 kHz to 130 kHz. The H plate crystal is used extensively for wide band filters (ordinarily below the E cut frequency range).   The temperature coefficient is linear and varies from about [-8 x 10^-6 /°C to -16 x 10^-6 /°C]. The NT cut can be designed within a frequency range of approximately 8 kHz to 130 kHz. The turnover temperature can be varied from +15 deg. C to +80 deg. C in most cases. The temperature coefficient for the NT cut is approximately -0.036ppm/°C². The XY bar is popular in the 3 kHz to 85 kHz range. Its smaller size than many other low frequency cuts, low impedance, and low Co/C1 ratio make it very popular. Real time clock applications are possibly the biggest user of this cut. The temperature coefficient for the XY bar is -0.033ppm/°C². The calibration, frequency at the reference temperature of high frequency crystals (AT, BT, and SC) to be within +/- 10 ppm and within several Hz for low frequency crystals is considered to be a tight tolerance, but with reasonable yields. Drive level must be limited in the application to prevent abnormal aging or damage. This drive level may need to be limited to 1 mW for high frequency crystals and as low as 0.1 mW for some low frequency crystals. Aging can also be affected by the mounting, imperfection in the quartz, and extended periods of time at high temperatures.

Ceramic resonators are generally used for less accurate applications. Initial accuracy (calibration) of these devices' ranges from ±0.05% to ±1.0%. Temperature stability is approximately 15 ppm/°C for ceramic resonators. Aging is in the range of ±0.5%/10 years. These devices are much lower Q than quartz crystals and also seem to be more prone to spurious modes of operation.

SAW (surface acoustic wave) devices are generally used in frequency ranges above that of the BAW (bulk acoustic wave) crystal such as the AT cut. All of the previously discussed crystals have been BAW crystals and thus the bulk of the quartz is involved in the area of excitation. The SAW involves only the surface of the substrate used. The frequency is set by the distance between the electrode "fingers" (see figure 8).
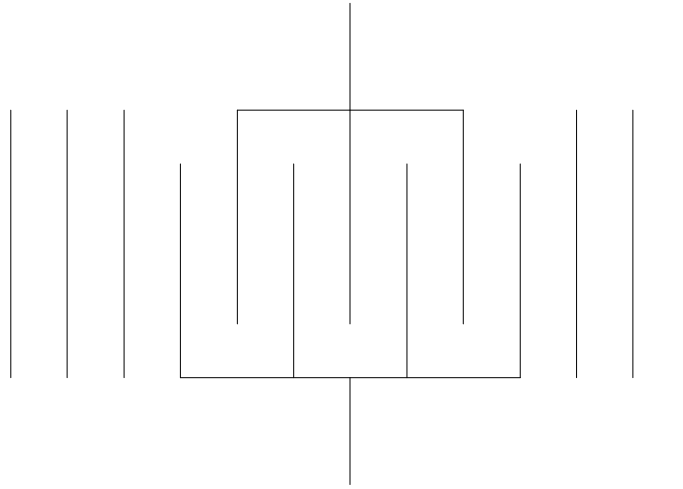
FIGURE 8

Quartz, LiTaO3, and LiNbO3 are common substrates for such devices. Initial accuracy is dependent on the accuracy of the printing of the "fingers". Initial accuracy can be in the ±50 to 200 ppm range. The approximate temperature constant of quartz is 0.03 ppm/$°C^2$ and -20ppm/$°C$ for LiTaO3. Upper frequencies of 3.5 GHz are currently obtainable. The lower end is limited primarily by size, since the AT becomes more practical.

Construction

The high frequency cuts (AT, BT, and SC cuts) are generally mounted on the edges using springs or channels mounted to the posts of the holder. The mass of the blank and the mechanical shock and vibration of the application must be carefully considered. If the mounting is too stiff, the blank will break more easily. If the mount has too much "give" for the mass of the blank, the blank will hit the holder and break. Strip resonators, which are usually AT cuts, have been used in much smaller packages than the disks used for the more conventional high frequency crystals. Because of this, manufacturers have developed numerous methods to mount these basically rectangular crystals. Because of their lower mass and smaller size, the mechanical shock and vibration is not as critical as with conventional high frequency crystals.

Low frequency cuts, instead of having relatively stable edges, have nodes which remain relatively motionless. These nodes are used for the electromechanical connection. Depending on the mode of vibration, there exist either one or two nodes on each of two sides. Thin wires are attached to these nodes and then the other end is attached to the posts of the packaging. This means that these crystals are suspended by two to four thin wires. Because of this and the mass of some of these very large crystals, it is obvious the mechanical shock and vibration of most low frequency crystals cannot be as high as the high frequency crystals.

To package a crystal, the following factors must be considered:
1.   A crystal vibrates, and thus requires air space around the area which vibrates.
2.   A crystal can be quite fragile, so mechanical shock and vibration of the application and handling are very important considerations.
3.   The crystal must be surrounded by an inert atmosphere. Thus, the package must be hermetically sealed.

Glass vacuum tubes and metal packages were, for many years, used exclusively for crystals. Still, one of the least expensive packages is made of metal. Sealing techniques for these metal packages can be resistance welded, solder sealed, or cold welded (a compression fit). Atmospheres inside must be void of moisture. Vacuum, nitrogen, or helium are commonly used. With the advent of the strip resonator, smaller packaging has been the focus of many companies. Some of the materials used recently are: ceramic, plastic, and glass. Ceramic or glass may be a good option as the seal is reliable and hermetic. To date, plastic is not hermetic and requires the crystal to be sealed in a secondary package inside the plastic.

Ceramic resonators are either dipped epoxy or plastic encapsulant similar to capacitors commonly used. SAWs are generally packaged in resistant welded metal packages.

Two sources for standard packaging for crystals are EIA (Electronic Industries Association) RS-417 and MIL-STD-683. Some of the common military type packages are HC-49/U, HC-25/U, HC-45/U, or HC-18/U for high frequency AT cut crystals, and HC-6/U, HC-33/U, HC-13/U, or HC-32/U for lower frequency crystals. EIA RS-192A can be used as a reference for standard package size for vacuum tube types. The EIA is also a good source of standard packages and registered packages which may be used in the crystal industry. Common packages must be used whenever possible to aid in developing multiple sources by preventing elimination of very good sources because of unavailable packages.

Application

For years now the electronic industry has used through hole packages (i.e., either packages with wire leads or sockets on the pc board and pins on the package). The wire lead option is still the most popular package type used. Although the frequency control industry is lagging the rest of the electronic industry, many manufacturers have developed surface mount packages. These packages are mostly used with the AT strip resonators. Some of the factors to consider are as follows:

Through hole:
1. Generally, assembly to the pc board is a hand operation.
2. Caution must be used when cutting the leads to prevent damaging the crystal inside.
3. Soldering operation must limit the heat to prevent reflow of any solder inside.

Surface mount:
1. Package standard has not yet been established.
2. SMD processes generally get the component itself hotter and thus aging is accelerated.
3. Repair is generally more difficult and may require special equipment.
4. Cost will be higher until a standard package is set and volume of usage increases. An important factor may be to select a package which fits into the flow of manufacturing already established for other components. Many of these factors listed above must be considered to prevent poor yields at the end of the process.

Specification

The most important factor in specifying a resonator or filter crystal is to know the circuit it will be used in. For digital devices, manufacturer's data sheets or application notes are generally very helpful in identifying the crystal requirements. Transistor and other active device oscillator circuits need to be evaluated carefully before specifying the crystal. Stray circuit capacitance and inductance can affect the actual operating point of the crystal greatly.

Specifications should include the following:
1.   The frequency of operation.
2.   Series or parallel mode of operation.
3.   If parallel, the load capacitance seen in the circuit.
4.   The maximum Motional Resistance for a series crystal or maximum Equivalent Series Resistance for a parallel crystal.
5.   Frequency tolerance at a reference temperature (calibration) and frequency shift over a temperature range (drift) or the frequency tolerance can be specified to include both in an overall tolerance allowing the manufacturer to trade off one for the other.
6.   Aging, or the amount of frequency shift over a long period of time, should be specified or included in #5 above.
7.   As discussed earlier, a standard package is preferred. The package must be compatible with the crystal required. A manufacturer may need to be consulted.
8.   Co, C1, or L1 requirements need to be specified if the circuit operation depends on it. Generally C1 or L1 need not be specified for oscillator circuits and Co is generally a maximum requirement. Oscillators which require the resonator to change frequencies (such as VCXO) will need to specify Co and C1 or simply specify the pullability (the frequency shift required with a specified change in load capacitance).
9.   The maximum drive level the resonator can expect in the circuit.
10.   Any mechanical shock or vibration the device will be exposed to in the application must be specified.

MIL-C-3098 can be used as a reference for many of these requirements, but it is a good idea to check with a couple of manufacturers for feasibility before finalizing the specification.

Testing

One simple, but not quantitative, way to test the crystal would be to place the crystal in the circuit. If this method is used, it is common to supply manufacturers with the circuit also for correlation purposes. This method can only verify the resonator functions and the frequency can be measured with a frequency counter. The CI-meter (crystal impedance meter) was designed to measure motional characteristics' R1, C1, and L1 of a crystal. Later models also measure the shunt capacitance (Co). The frequency of operation is measured by adding a frequency counter. It is possible to measure the frequency of operation of a parallel resonant device by simply placing a capacitor of the value of CL in series with the crystal and then placing this combination into the CI-meter. This type of active tester has been improved and expanded upon (such as Saunders and Associates) in recent years. Some of the improvements include direct reading of R1, automatic insertion of the load capacitance, etc.

Two methods of passive measurements have been developed into standards for crystal measurement. One is the EIA-512, which uses a Network Analyzer (or similar type equipment). In this method the signal and measurement devices are connected directly to the crystal. The other (developed in Europe) is the IEC#444. This method is very similar to the EIA-512 except that it uses a pi-network to connect the crystal to the signal and measurement devices. Both methods measure phase and impedance versus frequency to calculate the crystal parameters. The detailed standards should be studied if these methods are to be used. To date at least one software program has been marketed to assist testing using the EIA-512 method of measurement.

OSCILLATORS

Oscillators require a resonator, per the previous section, and an active device. Typically additional resistors and capacitors are also required in the circuit.

Theory of operation

Two requirements must be fulfilled in order to obtain oscillation in the closed loop circuit:
1.   The closed loop gain must be greater than or equal to one.
2.   The phase shift around the loop is $N*360°$, where N is an integer.

In addition, it is important to note that at power up the noise of the component around the oscillator circuit is what actually starts the oscillation. Some of the active devices used are discrete transistors, Field Effect Transistors, Op-Amps, and digital gates. A common transistor circuit is shown in figure 9 (colpitts oscillator).
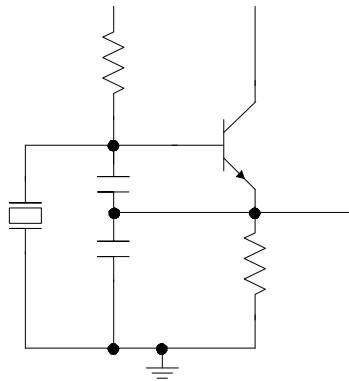
FIGURE 9

A typical digital gate circuit is shown in figure 10.

FIGURE 10

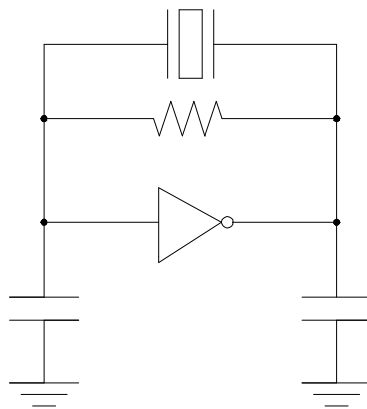Matching the resonator to the oscillator circuit is the responsibility of the manufacturer. In designs where the crystal is not enclosed before it is married with the oscillator circuit, the manufacturer can final adjust in the circuit. This eliminates the frequency shifts due to circuit variations. The oscillator circuit is typically buffered so variations in load do not greatly affect the frequency stability.

Characteristics

Clocks are a subset of the general crystal oscillator (XO) type. Clocks are usually used to supply frequency timing to digital circuits and microprocessors. Clocks are typically available in the same technology as any other digital IC's such as TTL, CMOS, ECL, etc. The frequency range of these clocks is primarily limited by the technology being driven such as 75 MHz for STTL, 125 MHz for 10k ECL, etc. The frequency characteristics are basically that of the crystal being used (AT cut is mostly used). Clocks can obtain calibration frequency tolerances of below ±10ppm. The oscillator circuit could add to the crystal drift depending on the temperature change of critical resistors, capacitors, or inductors in the oscillator circuit. Typically the circuit will be insignificant in the frequency variation. The clock is the simplest of all the oscillator types. Because of this, they are smaller, cheaper, and uses less power to operate than other types. Start-up time (the time it takes to start the oscillator once power is applied) ranges from under 1 msec. to 20 msec. The clock oscillator generally requires only one power supply voltage for operation.

VCXO, or voltage controlled oscillators, can have the output frequency change with a change in voltage at a control pin of the oscillator. VCXOs are used in many applications such as telecommunications, TCXO, or phase locked loops. The amount of frequency shift with a given voltage change (pullability) is highly dependent on the oscillator circuit. Pullability of 35 to 50 ppm/volt are common and higher pullabilities are obtained by adding an inductor to "de-Q" the crystal. Most, if not all, VCXOs use varactor diodes to vary the frequency. The varactor diode changes the capacitance across its terminals based on the DC (or low frequency AC) voltage across the same terminals. The frequency calibration and drift are basically that of the standard clock oscillator. Calibration may be degraded somewhat by the additional variable of setting the control voltage where this calibration is defined at. Since the crystal load capacitance is varied by the varactor diode, the drift over temperature varies from one end of the control voltage to the other. Thus, the drift can not be optimized for all control voltages. Those circuits that require "de-Qing" the crystal will have worse drift than the crystal by itself.

TCXO (temperature compensated crystal oscillator) adjusts the frequency for temperature variation. An integral part of a TCXO is a VCXO. Connected to the VCXO is generally a network of thermistor designed to bias the voltage control of the VCXO properly for each temperature. Recently, other compensation techniques have been used such as digital processing. TCXOs commonly have an outside adjustment for setting the calibration frequency periodically. This is to compensate for the aging of the crystal over time. The period between calibration will depend on the accuracy required and may range from once a month to once a year. Frequency drift can be expected to be in the ±1 to 5ppm range. Some of this tolerance comes from frequency versus temperature hysteresis (i.e., the difference in frequency at a particular temperature depending on whether the temperature was increasing or decreasing. Power dissipation is typically two to three times that of a standard clock oscillator. The size and cost of these devices are also larger than a standard clock oscillator. After power-up it could take as much as 100 msec or more for the frequency to stabilize in a TCXO. The TCXO may also require multiple power supplies depending on the design.

OCXO, oven controlled crystal oscillator, uses an oven to stabilize the frequency variation. The oven contains, at a minimum, the sealed crystal. The oven temperature, to maintain control, must be higher than the maximum ambient temperature expected in the application. The crystal is selected so that it has nearly zero frequency change in the range of temperatures expected in the oven (usually less than ±5°C). Frequency tolerances of much less than ±1ppm are realizable with an OXCO. Additional circuitry is required to control the oven and maintain the proper temperature inside. Customarily, similar to the TCXO, a calibration must be done periodically to compensate for crystal aging. A separate power supply is used for the heater in the oven. Isolation between this supply and others required by the oscillator must be established because of the noise generated when the heater is activated. The power required is considerably higher than a standard

clock oscillator (as high as several watts of power). Again, cost and overall size is much more than that of a clock oscillator (as much as 40 times the cost and size). OCXOs are popular as timing standards in the instrumentation market in such measurement equipment as frequency counters, spectrum analyzers, network analyzers, etc.

Another variety of "XO" type of oscillator has a sine-wave output. The output is generally specified into a fixed load and has a harmonic distortion specification. The sine-wave oscillator usually incorporates an AGC (Automatic Gain Control) circuit to ensure constant amplitude. Usually the TCXOs and OCXOs are also sine-wave outputs.

Two other types of oscillators, more recently developed, are the MCXO (Microcomputer Compensated Crystal Oscillator) and the DCXO (Digitally Compensated Crystal Oscillator). As their names imply, both compensate for the frequency shift with temperature. Either may be capable of improving on the TCXO performance without a large power usage.

Combinations of the above oscillators have been developed for some special applications. A TCVCXO is a Temperature Compensated, Voltage Controlled Crystal Oscillator and an OCVCXO is an Oven Controlled, Voltage Controlled Crystal Oscillator.

With the ability to put more complex circuits in an IC has enabled IC vendors to produce phase locked loop devices. Although a recent development, they are becoming increasingly popular. They basically use a stable crystal oscillator as a reference to a VCO or VCXO and a feedback loop. This design gives an output close to the stability of the crystal oscillator, but with various dividers can produce various output frequencies which are digitally selectable. This design is becoming very popular in the video market and other applications previously requiring multiple oscillators.

Construction

The Crystal Industry has long been innovative in packaging. All packages are hybrids of various packaging/hybrid techniques.

The common clock oscillator generally uses a thick film circuit printed on a ceramic substrate. Discrete components are either soldered or epoxied to the circuit. High temperature solder must be used, if soldering is done, to prevent the components from letting loose when the clock is soldered to the PC board. ICs are usually placed in DIE form and wirebonded, or procured in SOIC-type packages and soldered in place. Since most clocks use the high frequency cuts (AT, BT, or SC), the crystal blank (disk) is mounted on the substrate without the crystal being sealed in a secondary package. Crystal mounting hardware ranges from solid metal blocks to springs to thin punched metal pedestals. For most applications, the hardware which has some "give" to it seems to be best for mechanical shock, mechanical vibration, and thermal shock. The substrate is mounted to a metal header and has a metal cover which is resistance-welded on.

Other more complex oscillators, such as TCXOs, VCXOs, and OCXOs, use much different techniques. Although recently some of the simpler VCXOs and TCXOs have utilized Application specific ICs and other high technology techniques to miniaturize them into similar packages as the clocks, most still use a common pc board, leaded ICs, and a sealed crystal. These are in a rather large metal base with a metal cover either screwed or soldered to the base. Sealing the entire package is not critical, since the crystal is sealed inside. Clock oscillators are available in two package sizes; one is in a hybrid DIP with 0.300 inch row spacings and 14 pin compatible, the other is the same, except that it is 8 pin compatible. Usually only the 4 corner pins are present, since the other pins are not required for either electrical or mechanical purposes (see figure 11).
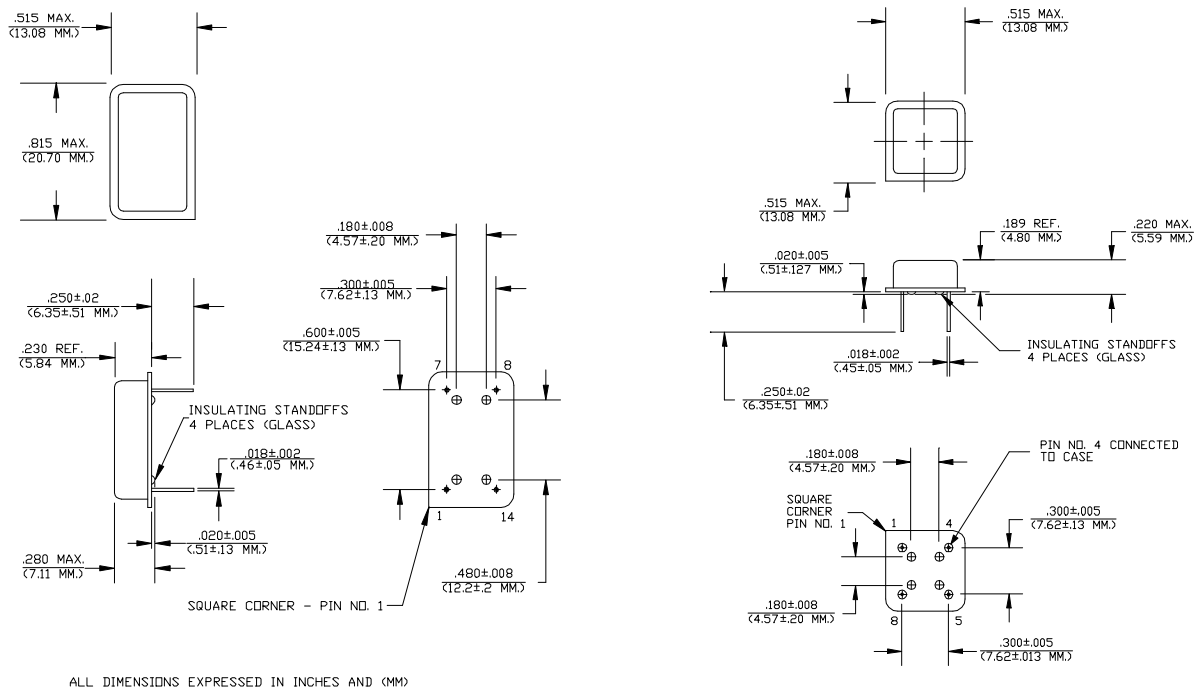
FIGURE 11

There seems to be very little standardization for the more complex VCXOs and TCXOs. They generally take up three to five times more PC board area than the smaller clock oscillators.

Application

The frequency control industry has made the metal hybrid resistance weld package a reasonably high volume/low-cost package option. Even today it is by far the most widely used package in either the 14 pin version or the 8 pin version. Although surface mount packages have been slow to come to the frequency control industry, many manufacturers have introduced a version or have one under development. Many manufacturers have offered an SMD version of the above metal package with a gull wing lead bend. This has not been accepted throughout the electronic industry as fulfilling the needs of a true SMD package. A number of true surface mount packages have been developed by a number of manufacturers. Most use either a plastic package with a secondary-sealed package inside (either just the crystal or the whole oscillator), or a ceramic package. None of the leaded surface mount packages are industry standards, but some are being evaluated by the EIA. Because of the complexity of the circuits, the TCXOs and OCXOs are available in through hole versions only.

A number of factors need to be considered when selecting through hole or surface mount packages:

Through hole:
1. Hand assembly of component to the PC board.
2. Soldering operation must limit heat to prevent reflow of any solder inside.

Surface mount:
1. Package standard has not yet been established.
2. SMD soldering process usually gets the component itself hotter and thus aging is accelerated.
3. Repair is generally more difficult and may require special equipment.
4. SMD packages will be higher cost until a standard is set and volume increases.

12

Other important factors are second source availability and how the oscillator package fits into an already existing flow of manufacturing. All of these factors, plus any special ones, must be carefully evaluated to prevent poor yields at the end of the process.

Specification

When creating an oscillator specification, it is important to consider what the application expects of the oscillator and not just "boiler plating" a specification. This practice could cause undo expense when purchasing the components.

It is common, and possibly easiest, to specify the frequency tolerance over all specified conditions such as temperature, voltage, calibration, etc. If individual requirements are to be specified, all expectations should be specified. Temperature drift, calibration, variation with voltage, variation with load, and aging are all frequency tolerances required to completely specify the oscillator. In addition, voltage controlled versions must also have frequency change with control voltage variation specified. It is important for the aging characteristic for the maximum operating or storage temperature to not be specified higher than necessary for the application. Unless otherwise specified, the aging requirement is assumed to be at $25°C$ or, at a minimum, the average temperature is $25°C$.

Whether the oscillator is a clock or a sinewave output, it is important to clearly specify the load that the oscillator will drive in the application. Load capacitance expected may be difficult, but necessary, to specify. The stray load capacitance on the PC board may be distributed over a trace inductance. In this case, an estimate will need to be made. Another problem area may be in using the TTL industry equivalent load at higher frequencies. The diodes customarily used in these loads do not switch fast enough to represent the actual faster TTL technology.

For clock oscillators, the digital waveform must be specified. The logic level limits expected into the specified load must be defined. These logic levels are basically defined by the specific device being driven or the technology of the device being driven. The Rise and Fall times or the speed at which the oscillator transitions between logic levels must be specified. The levels at which these measurements are taken need not be the logic levels. The symmetry (duty cycle or squareness) is normally specified as the time the output is higher in voltage than the threshold voltage of the device being driven over the period. The threshold voltage must be between the logic low and the logic high.

For oscillators with sinewave outputs, the output waveform characteristics must be defined. The amplitude of the sinewave output is usually expressed in volts peak to peak, or in dBm. Harmonic distortion (the amplitude of the portion of the signal which is at three times, five times, seven times, etc. of the main output frequency) is specified in dB below the main output frequency. In some cases, it is desirable to specify a noise level or non-harmonic distortion. This is useful to limit distortion due to such techniques as doubling (this may produce a distortion at 1.5 times).

All oscillator specifications should limit the power or power supply current to the amount available to the oscillator. Breakdown voltage or absolute maximum power supply voltage must be specified (most digital gates require less than 7.0 volts). Start-up time after power is applied should be included in the specification. Another important parameter, especially in overtone oscillators (oscillators over 25 MHz may use overtone crystals), is the range of time it takes the power supply to ramp up to operating voltage seen during testing and in the application. Very long or very short power supply ramp-up times may cause the oscillator to start and operate on the wrong mode of the crystal (in the fundamental instead of the third overtone, or the fifth overtone instead of the third overtone). Some of this affect is due to critical filtering condition. Also involved is the active device characteristic known as gain-bandwidth product which is lower at lower voltages, and higher at higher voltages. Thus, this gain-bandwidth is changing considerably during power up. Phase noise or phase jitter has become an important parameter recently. Phase noise or jitter is the short term variation in the period. This characteristic can be specified either in the frequency domain or the time domain. The actual specification will depend greatly on the application and should be worked closely with the manufacturer.

The mechanical shock and vibration the device is expected to withstand must be specified. Also, any other special application conditions or requirements not listed above should be in the specification if it might affect oscillator performance expectations. Some other examples of parameters needed may be power supply isolation, signal overshoot, or signal undershoot.

Testing

Most of the basic measurements of a clock oscillator can be measured using a frequency counter to measure frequency, a current meter or DVM to measure power supply current, and an oscilloscope to measure the voltage levels, rise and fall times, and symmetry. In some cases, a Time Interval Counter can replace the frequency counter and oscilloscope. The same setup can be used for a sinewave oscillator if the output is defined as peak to peak voltage. If the sinewave oscillator output is defined in dBm, then a Spectrum Analyzer is required. In most cases, the Spectrum Analyzer is required to measure the distortion of a sinewave oscillator.

The bandwidth of the oscilloscope or input stage of the time interval counter is important to the accuracy of the waveform measurement. In the case of the clock oscillator, the ideal waveform would be a square wave. The square wave is made up of sinewaves at the fundamental frequency (the output frequency specified) and all of the odd harmonies of that frequency.

Since the amplitude, or the amount each harmonic contributes diminishes as the harmonic order increases, the lower orders are most important in our waveform measurements. If the clock oscillator output frequency was 50 MHz, then the oscilloscope bandwidth must be 150 MHz minimum to adequately involve the third harmonic in the measurement. Also, this minimum bandwidth must be a combined oscilloscope and probe bandwidth. If overshoot or ringing in the waveform is critical to the application, the oscilloscope bandwidth may be set by this rather than the oscillator frequency. It is common for overshoot to have a duration of approximately 1 nsec. If this is assumed to be approximately one-half of its period, the period would be 2 nsec. and the frequency content would be 500 MHz. Thus, the minimum combined bandwidth of the oscilloscope and probe becomes 500 MHz.

Fixturing for clock oscillator testing is becoming a critical factor in measurement ability as output frequencies rise. Sinewave oscillators are generally specified into 50 or 75 ohms and can utilize a clean transmission line for interconnection. But, TTL or CMOS type of outputs for the clock oscillators cannot utilize the standard transmission lines. For these applications it is important to minimize stray fixture capacitance. Keep the load and test points as close to the oscillator output as possible. It is very important to use good RF circuit techniques when building oscillator test fixtures as well as the actual application circuit. As noted earlier, the industry TTL equivalent load uses diodes which may not be adequate for higher frequencies due to switching times. Before using faster diodes, the customer and manufacturer must agree on the change.

The power supply ramp-up time should be known for the test equipment being used to power the oscillator. The power supply ramp-up time must be within any limits set in the specification. In some cases start-up may be verified at each extreme if specified. Various methods are used to control this. One is to use a simple RC time constant in the power supply line. Another is to use a waveform generator to drive the oscillator's power supply line.

In general, crystal oscillators are simpler to use in a design and require more traditional test equipment than a discrete crystal. The crystal oscillator also puts more of the design and verification burden on the manufacturer.

References:

Raytheon Saw Devices Technology 1/87.

Toyocom Saw Devices 1989/1990.

Sawtek Saw Scene summer 1986.

NTK Technical Ceramics 1985.

Fujitsu Acoustic Resonator data sheet

NEL Catalog 380(1982)

NEL Catalog 9001

Quartz Crystal Resonators and Oscillators,
a Tutorial by John R. Vig
Available for downloading in the Tutorial section at http://www.ieee-uffc.org/fc

Introduction to Quartz Crystal Unit Design
 by Virgile E. Bottom, Ph.D.
VanNostrand Reinhold Company

Design of Crystal and Other Harmonic Oscillators
 by Benjamin Parzen/Arthur Ballato
John Wiley & Sons

Crystal Oscillator Circuits
 by Robert J. Matthys
John Wiley & Sons

Handbook of Piezoelectric Crystals for Radio Equipment Designers
WADC Technical Report 56-156
 by John P. Buchaman
Office of Technical Services,U.S. Department of Commerce.

EIA-512
Electronic Industries Association
Engineering Department
2001 Eye Street,N.W.
Washington, D.C. 20006

IEC#444
International Electrotechnical Commission
1,rue de Varembé
Genève,Suisse