Specifying Crystal Oscillators

INTRODUCTION

ISOTEMP RESEARCH specializes in providing custom and semi-custom oscillators. We have focused our efforts on OCXO's and high performance NCXO's, VCXO's, and TCXO's. This application note is designed to help our customers understand the parameters used in specifying a crystal oscillator.

GENERAL

When specifying a crystal oscillator, it is important for the supplier to understand the requirements. The underlying requirement is usually some stability of frequency or time. This stability information needs to be conveyed to the supplier along with the maximum changes that will be seen by the oscillator in its environment. Some of these changes are: operating temperature, voltage, load, altitude, shock, vibration, number of times turned on and off, humidity, and storage temperature. In addition, there will be other stability requirements such as phase noise and short term stability. Other parameters of specifying an oscillator are: r.f. output type and level, amount of time allowed after power on for the oscillator to meet the stability requirements, type of frequency adjustment and range, power availability, and noise emitted by the oscillator. Some other functions available are: oven monitor and reference voltage.

These requirements should have an order of importance during the initial quotation process. The order of importance will allow the supplier and the customer to make trade offs if necessary and to come up with the most cost effective solution. The overall goal is to get the total of the stabilities to be less than the requirements. Obviously an oscillator with no deviations in temperature, time, voltage, etc. would be the ideal solution. However, some requirements are mutually exclusive and sometimes compromises are needed. Table 1 lists most of the different types of crystal oscillators available.

TABLE 1

Nomenclature	Description
XO	Crystal Oscillator. At ISOTEMP we use the nomenclature of NCXO for all Non Compensated Crystal Oscillators.
VCXO	Voltage Controlled Crystal Oscillator
TCXO	Temperature Compensated Crystal Oscillator
OCXO	Oven Controlled Crystal Oscillator
MCXO	Microcomputer Compensated Crystal Oscillator

Some of the oscillator nomenclatures can be combined, i.e., TCVCXO: Temperature Compensated Voltage Controlled Crystal Oscillator and OCVCXO: Oven Controlled Voltage Controlled Crystal Oscillator. At ISOTEMP we only use the four letter nomenclatures because most oscillators require some type of frequency adjustment (electrical or mechanical) to adjust for aging.

The two largest instabilities in oscillators are frequency verses time and frequency verses temperature. Table 2 lists the approximate stabilities for each type of oscillator listed in Table 1. Advantages and disadvantages to each type of oscillator are listed in Table 3.

TABLE 2

Oscillator Type	Frequency verses Temperature (0°C to 70°C) (PPM)	Frequency verses Time (1 year) (PPM)
NCXO	5 to 100	1 to 10
VCXO	5 to 100	1 to 10
TCXO	.1 to 5	.1 to 2
OCXO	< .001 to 1	.02 to 2
MCXO	< .05 to 2	.02 to 2

TABLE 3

TYPE	ADVANTAGES	DISADVANTAGES
NCXO	Low power. Minimal warm up time. Least expensive crystal oscillator. Much higher frequency stability than a LC or ceramic oscillator.	More PCB space than a LC oscillator. Poor temperature performance as compared to TCXO’s and OCXO’s
VCXO	Low power. Minimal warm up time. Can be locked to an external source. Provides good local short term stability.	High frequency adjustment range could degrade temperature performance to less than an NCXO. Poor temperature performance as compared to TCXO’s and OCXO’s
TCXO	Low power. Short warm up time as compared to an OCXO. Good temperature performance.	More expensive than NCXO’s and VCXO’s. Requires more PCB space than most NCXO’s and VCXO’s.
OCXO	Best stability available for a crystal oscillator. Superior: Phase noise, temperature performance, aging, etc.	Largest package size of any oscillator. Has the longest warm up time. More expensive than TCXO’s.
MCXO	Low power as compared to an OCXO. Short warm up time as compared to an OCXO. Good temperature performance.	Higher cost with today's technology as compared to an OCXO. Increased noise due to digital switching.

The cost order does overlap in certain areas where the technology of that type of oscillator is pushed to its limits. Some examples are:

A ± 0.1 PPM temperature requirement is usually less expensive as an OCXO than a TCXO.

A wide pull range VCXO (i.e., ± >100 PPM) will usually cost more than a standard TCXO.

PARAMETERS

The following sections are general guidelines to help specify a crystal oscillator. A section may be omitted from the specification if that parameter is not critical to the application. Specifying less will help keep cost under control. However, there should be minimum requirements on some specifications and some specifications will come naturally because of other parameters. Let us know if you have statistical information requirements on certain specifications.

Parameter Name **Description**

OUTPUT

FREQUENCY

Obviously a frequency needs to be specified. However, sometimes it is more cost effective to get an oscillator at a multiple of the desired frequency.

FREQUENCY AT TIME OF SHIPMENT

To reduce production test and calibration, many customers request that the oscillators are received within a specified frequency window or tolerance. This frequency tolerance is specified after some period of warm up. Knowing this tolerance, ISOTEMP can set the oscillator within the specified after warm up tolerance. However, when the oscillator is received, the frequency will not be the same as when the oscillator left ISOTEMP. This frequency difference can be attributed to: 1) the overall oscillator stability, 2) time off power, 3) shipping, 4) test conditions at the customer, and 5) retrace. The frequency tolerance can range from 0.02 PPM to 0.3 PPM. Contact ISOTEMP Engineering for further application-specific information.

WAVE FORM

The types of wave forms available are: Sine wave, Rectangular, Clipped Sine wave, and ECL. The two most popular outputs are sine wave and rectangular. For sine wave output a higher load impedance and lower level will require fewer buffering stages, reduce the internal parts count, and consume less current. Additionally, TCXO's with a higher load and a lower output level will have a reduced warm up time. Units with a rectangular wave form usually use a buffering device from the HCMOS family. (ACMOS, HCMOS, CMOS, etc.) With a rectangular output, internal division is easily done and gives ISOTEMP design flexibility.

LEVEL

For sine wave units output levels are available up to +20 dBm. For units with loads other than 50 ohms there is a lot of flexibility in the output level. The maximum level is determined by the input voltage, package size, and input power. The most cost effective way to specify an output level is to specify a minimum. However, depending upon the level required and the internal oscillator design, the level can be specified with a tolerance of ±0.5 dBm or ±5%.

For rectangular wave form units, the levels are those specified by the chip manufacturers. Refer to the data books for the family type and output level for the requirement.

LOAD

For sine wave units almost any load is possible. If the load is non-resistive, the actual load should be specified. (E.g., 510 ohms in parallel with 15 pF)

For rectangular wave form units the load should be specified for the family type and fan out that will be connected to the oscillator. To reduce the size of our oscillators, we use IC's that are not capable of driving the full fan out that many families specify. A fan out of one or two loads is desired and will give more design flexibility. If the oscillator is not driving the load for any particular IC family, the actual load should be specified.

HARMONICS

For sine wave units a specified harmonic content of <-20 dBc is easily obtainable. The harmonic content is determined by the output power, input voltage and current, and number of internal buffering stages. Often, <-35 dBc is obtainable without a cost increase.

DUTY CYCLE

For rectangular wave form units a duty cycle of 40% to 60% is standard. 45% to 55% is easily obtained in most designs, and 48% to 52% is available in special cases.

RISE/FALL TIME

For rectangular wave form units the rise/fall time is dictated by the load and the type of output device used in the oscillator. A quick rise/fall time may put restrictions on the output buffer required to meet the specification.

SPURIOUS

Spurious oscillations of < -60 dBc is standard and covers a spectrum from 100 kHz to 1 GHz. Tighter spurious responses should be specified over a specific spectrum.

SUB-HARMONICS

Sub-harmonics are usually not specified, and we only specify them where we are multiplying the frequency to obtain the desired output. If sub-harmonics will be detrimental to the application, they should be specified.

FREQUENCY STABILITY

TOTAL

A total frequency stability verses the particular requirements may be specified. This parameter is a good way to convey the requirements needed in the end application. (E.g., < ±0.1 PPM/ day for temperature, voltage, and load.) Sometimes the end application will not experience the total changes as called out in other areas of the specification. (E.g., The input voltage tolerance is ±5% as dictated by the tolerance of the voltage supply to the oscillator. However in system, the supply voltage may only change ±1% due to effects of the load, temperature, etc.) Therefore, this requirement may be specified over particular changes of other parameters.

AMBIENT (TEMPERATURE)

This parameter has a considerable effect on the overall stability of the oscillator and should always be specified. It can be specified as a peak to peak window over the operating temperature range, or as a zero to peak movement referenced to a particular temperature, or a frequency change per degree of temperature. For NCXO's and VCXO's the characteristic of this parameter follows the curve of the crystal, a third order polynomial. For TCXO's the characteristics usually follow a third or higher order polynomial. For OCXO's the characteristics usually follow a first or second order polynomial. At ISOTEMP we usually specify a zero to peak movement with a reference temperature. Usually this requirement is specified under static conditions. If the requirements are under dynamic conditions such as rapid temperature changes, these changes should be specified.

AGING (TIME)

In addition to the ambient performance aging also has a considerable effect on the overall stability and it should always be specified. The aging rate should be specified after a specific period. For most oscillators the aging more closely resembles a straight line on a semi-log plot with time being on the log scale. Because of this logarithmic characteristic, the aging rate is specified over one or more periods of time (Day, month, year, and XX years.) For ovenized oscillators an aging rate at time of shipment is also specified. Oscillators will age when left un-powered but not as much as when energized. The off power aging sometimes dictates specifying aging after storage. For more information on aging see ISOTEMP application note CRYSTAL OSCILLATOR AGING (146-000).

VOLTAGE

The voltage stability of an oscillator is also an important parameter. If this parameter is too loose, it will show up as changes in other parameters such as ambient and initial frequency tolerance. If multiple input voltages are used, this parameter should be specified for each voltage. If the input voltages change together, this information should also be conveyed on the specification.

SHORT TERM

The short term stability is the change in the oscillator's frequency when measured with a counter. Short term is usually specified by calculation method and time interval. ISOTEMP usually specifies the short term by the calculation method of the Allan variance, but RMS, peak to peak, and others can also be specified.

LOAD

The frequency change verses the change in load for an oscillator is usually not a large consideration, except on sine wave units where minimal buffering is available. A reactive load change will affect the frequency more than a resistive change. For most sine wave units the load stability is specified for a ±5% change in a resistive load. If the load will be reactive, the possible impedance change should also be specified. For rectangular output units the load is usually specified for a one gate change.

WARM UP

All oscillators experience some frequency change during initial power on. For TCXO's the change is minimal and is usually masked by the temperature performance. For VCXO's and NCXO's the warm up characteristic is seen as the internal components warm up and cause the frequency to follow the crystal curve. Warm up is usually not specified for non-ovenized types. OCXO's have the largest frequency movement during initial power on (typically 40 PPM at 25°C.) For all oscillators except OCXO's the frequency will usually stabilize in less than 15 minutes and the warm up period will not change much with temperature. However, for OCXO's the time can vary a great deal depending upon the temperature and the type of design. For more information on OCXO warm up see ISOTEMP application note UNDERSTANDING OVENIZED OSCILLATORS (146-003). Warm up is specified as a frequency at some point in time referenced to the frequency at a later point in time measured at the same outside temperature.

PHASE NOISE

Single side band phase noise is the signal to noise ratio measured in a 1 Hz bandwidth at a frequency offset from the carrier. The phase noise of an oscillator is tightly coupled with other parameters. The short term stability of the oscillator is a function of the phase noise. When a low phase noise unit is specified, the unit will also exhibit good aging and temperature performance. Phase noise is usually specified in dBc at certain frequency offsets from the carrier. When more than one frequency offset is specified, the noise of the oscillator must be below the line connecting these points when plotted on a semi-log plot with frequency offset being on the log axis.

RETRACE

Retrace is the degree to which an oscillator will repeat its frequency after being turned off for a specified amount of time. Retrace is in the $1x10^{-8}$ range and is usually not specified except for very high stability OCXO's. In order for other parameters not to mask this characteristic, a sufficient pre and post power off period should be specified and other influences such as voltage and temperature should be held constant.

HUMIDITY

Open frame and non-sealed units will change frequency with humidity. If the oscillator will experience high humidity levels, a sealed unit should be considered.

MECHANICAL STRESSES

One of the most fragile parts in an oscillator is the crystal. Think of the crystal as an electro-mechanical part. Unlike other electrical components that manipulate electrons without any physical movement, the crystal is physically moving at the oscillating frequency. Therefore, any physical movements to the crystal will cause a change in frequency. This frequency shift may be temporary or permanent depending upon the level of the movements the crystal experiences. The frequency change will be different for each axis. The most sensitive axis is in the plane of the crystal blank in the oscillator. Temporary frequency shifts are associated with crystal blank mounting stresses and the flexing of the crystal blank. Permanent frequency shifts are associated with the crystal blank mounting structure permanently changing the mounting stresses on the crystal blank. Catastrophic failures occur when some part in the crystal unit breaks (Mounting structure, epoxy, or the crystal blank.) Therefore, all oscillators will have associated frequency instability due to shock and vibration. These instabilities are specified in the following ways:

SHOCK, ASSOCIATED FREQUENCY SHIFT

The before to after frequency change due to a shock or series of shocks in one or more planes either on power or off power.

SHOCK SENSITIVITY

The frequency short term stability caused by a shock in one or more planes.

VIBRATION, ASSOCIATED FREQUENCY SHIFT

The before to after frequency change due to vibration in one or more planes occurring on power or off power.

VIBRATION SENSITIVITY

The frequency short term stability or phase noise caused by vibration in one or more planes.

ACCELERATION SENSITIVITY (2-g TIP OVER)

The frequency change with the oscillator's relative position to the pull of gravity. Frequency change caused by turning the oscillator upside down. This is the zero frequency VIBRATION SENSITIVITY.

MICROPHONICS

A way of specifying SHOCK SENSITIVITY and/or VIBRATION SENSITIVITY without elaborate shock and vibration equipment.

FREQUENCY ADJUSTMENT

RANGE

The range of the frequency adjustment should be specified to cover all the oscillator's instabilities for the life of the oscillator, the largest is usually aging. Since aging is not a linear function, the range should not be the yearly aging rate times the life. The XX year aging plus the other stabilities will be sufficient for this specification. If the system requirements or design require a wider range, this wider range should then be added to the total above.

MECHANICAL

RANGE

Only a minimum range should be specified. The resolution will dictate the maximum range. Also see FREQUENCY ADJUSTMENT, RANGE.

COARSE RANGE

If the requirements demand that the unit be set to a frequency tighter than what is capable from a unit with a single adjustment, a course and fine mechanical frequency adjustment will be required. The coarse adjustment should follow the rules in FREQUENCY ADJUSTMENT, RANGE.

FINE RANGE

The fine range should be sufficient to cover the resolution of the coarse adjustment.

RESOLUTION

The resolution is dictated by the maximum design range and the number of turns of the trimmer. Any technician can set the trimmer to within 10 degrees without a problem. If the requirement necessitates tighter than 10 degrees of rotation, excessive time will be spent setting the oscillator to frequency.

CONTROL

At ISOTEMP we use many different trimmers with the number of turns varying from ½ turn to 25 turns. Using a multi-turn trimmer makes the oscillator much easier to set to frequency.

ELECTRICAL

NOTE: Caution must be taken on PCB design when ELECTRICAL frequency adjustment is used. Besides the VCO port picking up noise, special attention needs to be given to the ground paths. Ground voltage build ups are of particular importance when the power fluctuates in the system. For a system with an OCXO the power will change with temperature. A few milli-ohms resistance difference between the oscillator ground and the electrical frequency controlling device may cause the oscillator to fail ambient. If the oscillator is socketed, the contact resistance should also be considered.

RANGE

The electrical frequency adjustment range is usually specified over a particular control voltage range. A minimum and maximum range should be specified. The maximum range will keep the frequency verses voltage sensitivity in check. If the oscillator does not have MECHANICAL FREQUENCY ADJUSTMENT, the range should be specified referenced to nominal frequency when the oscillator is new. If the oscillator does not have MECHANICAL FREQUENCY ADJUSTMENT or the system design requires no calibration of the MECHANICAL FREQUENCY ADJUSTMENT, the range should be wide enough to cover aging plus any modulation and/or the stability of any external reference source. If the oscillator does have MECHANICAL FREQUENCY ADJUSTMENT, this range should be referenced to the CENTER VOLTAGE. Also see FREQUENCY ADJUSTMENT, RANGE.

CONTROL

Control specifies how the ELECTRICAL FREQUENCY ADJUSTMENT will be controlled. This control specifies the voltage range and/or pin connections for an external trimmer for the electrical frequency adjustment.

SLOPE

Slope specifies positive or negative frequency verses voltage for the electrical frequency adjustment.

CENTER

Center specifies the voltage and tolerance at which nominal frequency will occur. On units with mechanical frequency adjustment a tolerance on the center does not need to be specified. For 99% of the oscillators at ISOTEMP the center voltage is held internally by an high impedance resistor network; therefore, the oscillator frequency is stable even if no voltage is applied.

LINEARITY

Linearity specifies how much the frequency verses voltage function varies from a straight line. This function is usually a second order polynomial. Most oscillators will have a linearity of $< \pm 20\%$.

INPUT IMPEDANCE

The input impedance of the electrical trim input is usually resistive and for most oscillators is > 50 k ohms. Specifying excessively high input impedances (> 200 k ohms) will limit design flexibility and affect production yields and phase noise.

FREQUENCY RESPONSE

The frequency response of the electrical adjustment is dictated by the Input impedance, the controlling varactor, and any capacitance designed into the electrical frequency adjustment biasing network.

INPUT POWER

The voltage and current requirements for oscillators vary greatly depending upon the oscillator type and frequency. OCXO's have the largest power variations. Therefore, they will be discussed separately.

NCXO's, VCXO's and TCXO's for the most part are constant current designs. These oscillators require a certain amount of current for operation independent of the input voltage. Many designs also have internal voltage regulators. Because most designs are optimized for operation at a particular voltage, a ±5% voltage tolerance is preferred. Additionally, a larger than ±5% tolerance at +5 VDC operation makes the design even more difficult.

In an OCXO, the oscillator section of the design has the same characteristics outlined above. However, the heater section of the design has two operating modes. At turn on, while the oven is warming up, the heater is in a constant current mode. After the oven reaches temperature, the input is in a constant power mode. This power varies with temperature. Since the heater control circuitry consumes little power compared with the heater and the heater consumes most of the power, many OCXO's have two voltage inputs: one for the oscillator section and one for the heater. Dual inputs offer the advantage of having a large voltage tolerance on heater input allowing the heater to run directly off an unregulated voltage. The dual inputs are advantageous for systems where overall power is a concern. Additionally, a separate oven input will put less requirements on the voltage regulator supplying the oscillator, saving system space and costs. For more information on OCXO power consumption see ISOTEMP application note UNDERSTANDING OVENIZED OSCILLATORS (146-003).

OTHER OUTPUTS

OVEN MONITOR

An oven monitor is an output that indicates that the heater in an OCXO has reached temperature (for most designs, the oven monitor toggles when the heater switches from the constant current mode to the constant power mode.) The point in time where the oven monitor toggles corresponds to a somewhat stable frequency. However, since there is a time lag between the heater temperature and the crystal temperature and the heater temperature is still approaching its final value, the frequency will not be its final value. There are two types of oven monitors: 1) A signal indicating the oven is below the operating temperature, 2) A signal indicating the oven is not at operating temperature (above or below.)

REFERENCE VOLTAGE

On some OCXO's and TCXO's with electrical frequency adjustment a reference voltage is available. Since on these types of oscillators a stable voltage is required in the design, a reference voltage comes at little cost. For OCXO's the internal voltage regulator is usually heated and offers temperature performance superior to external voltage regulators. The voltage verses temperature will be in the range of a few PPM per °C. Since this voltage is manipulated and fed back into the VCO port of the oscillator, the following parameters need to be considered when determining the ambient performance of the oscillator: VOLTAGE, LOAD, AMBIENT, REGULATION, temperature coefficient of VCO port controlling device.

EMITTED NOISE

All oscillators will inject some noise back onto the supply line. This noise will be a current surge at the output frequency and the internal frequencies of the oscillator. In some cases this noise may cause problems in the system and may need to be specified. If the emitted noise will be a concern in the system, contact ISOTEMP Engineering for more information.

ENVIRONMENTAL and PRODUCTION PROCESSES

STORAGE TEMPERATURE

Crystal oscillators are assembled using commercially available components and epoxies. The limiting factor in the maximum storage temperature is the epoxies and should be limited to +105°C. The limiting factor in the minimum storage temperature is the electronic components and should be limited to -50°C.

SEAL AND CLEANING

If the oscillator is going to be cleaned by an automatic cleaner or immersion, a seal should be specified. Solder sealed units will meet MIL-STD-202, Method 112C, Test condition D. This test is a bubble leak test and is sufficient for most cleaning methods. If an open frame unit is being considered, contact ISOTEMP sales for recommended cleaning methods.

OPERATING TEMPERATURE

If the oscillator is required to operate outside the specified Frequency verses temperature range, an operating temperature range should be specified. The oscillator will continue to operate, but it will not hold any stability specifications.

TEST DATA

A prerequisite to supplying quality products is having checks during the production process. ISOTEMP uses these tests to find and resolve process variations before they become a problem. While performing test steps, data is recorded and used for process centering. On many units there is also out-going verification of some specified parameters. The parameters critical to function, the statistical soundness, and product quantity dictate what type of data is taken. Contact ISOTEMP sales for the data and data type available. If the data is part of our regular processes, ISOTEMP will provide it at no charge.

DATA STORAGE

Most data is stored on computer and all data obtained during production processes is stored for a minimum of two years.

MARKING

Most of ISOTEMP’s product is marked with a Label. Many products have a label overlay to protect the marking during cleaning.

MECHANICAL

See an ISOTEMP catalog for available packages. We offer many different sizes of NCXO’s, VCXO’s, TCXO,s and OCXO’s. If a package is not listed that meets the requirement, contact ISOTEMP SALES. We are continually developing new packages.

CONCLUSION

This application note does not list all of the possible parameters used to specify a crystal oscillator; however, it provides a good starting point for customers new to crystal oscillators. Specifying an oscillator can be very involved, but one must remember that all of these parameters may not be needed. Over or under specifying a unit can end up being very costly. Through awareness and communication, we can work together to fulfill your requirements. At ISOTEMP we pride ourselves on supplying quality service and products. We will give you the best value obtainable anywhere. By working with you and understanding your requirements, we will meet or exceed your expectations.

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REFERENCES

MIL-O-55310B Military specification for crystal oscillators.
U.S. government

For further information on the specification and application of Ovenized Crystal Oscillators, please contact the sales or engineering staff at Isotemp Research, Inc. For reprints of this article, ask for document number 146-010.

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Isotemp Research Inc. is an American company building performance ovens and oscillators since 1968