VCXO Basics

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Overview

VCXO, or Voltage Controlled Crystal Oscillators are wonderful devices – they function in feedback systems to pull the crystal operating frequency to meet a target closed-loop response while maintaining a clean clock output. They are essential when you begin to approach systems that require frequency tracking such as a Set Top Box tracking from Satellite or a Cable feed. There are many applications for a VCXO, in the end it all boils down for one system to accurately track another.

By today's standards, VCXO's are ubiquitous in the engineering design world. The notion of "pulling" a crystal to offset the frequency is by no means a new concept; in fact, on the surface it really is an extension of fixed capacitive loading to variable. The concept of variable loading is simple on the surface, but design pitfalls can be a real problem when so little is ever published on the nature of these devices -- specifically on *what* can go wrong. Oftentimes VCXO clues to misbehavior were there all along; but are often glossed over as simple measurement errors or perhaps considered inconsequential. Maybe you are one in the lucky crowd never confronted with a system catastrophic failure. While a misbehaving VCXO will bring down the whole system, the trick will be to prove that the VCXO *is* the culprit – easier said than done! Good detective work requires that you have a grasp of the fundamental problem which leads to better engineering solutions rather than just choosing another crystal or VCXO circuit that makes the thing "work" (only to be changed by someone else in production to save cost). All this leads to a brief overview of oscillators and VCXO technology along with terms of convention. Following this, we will delve into murky waters in search of clues as to what makes a VCXO behave, well, less that expected.

The VCXO introduces to the system a mechanism to adjust frequency output as a function of an input voltage (or current) control. The control voltage is most likely the result of an error control voltage extracted from say, the demodulation process. The relationship between the control input and output frequency most typically does not follow a 1:1 relationship across the full operating range of the control input. Common practice in VCXO programming is to provide frequency "roll-off" as you reach the operating boundary -- creating a soft entry to the boundary frequency. VCXO programmability allows customization of the transfer function. Well-crafted systems always exhibit smooth and clean frequency transitions as the control signal varies over the *full* operational range. Examples of good VCXO system design ensure that a well-balanced slewing range surrounds the VCXO center operating frequency. Figure 1 illustrates a classical example of the VCXO pull curve. The vertical axis denotes frequency offset from the *normalized* or center frequency expressed in PPM or parts-per-million. The horizontal is representative of the swing of the control voltage. Note how the curve behaves monotonically at all points, and “softens” as it rolls slowly to boundary conditions.

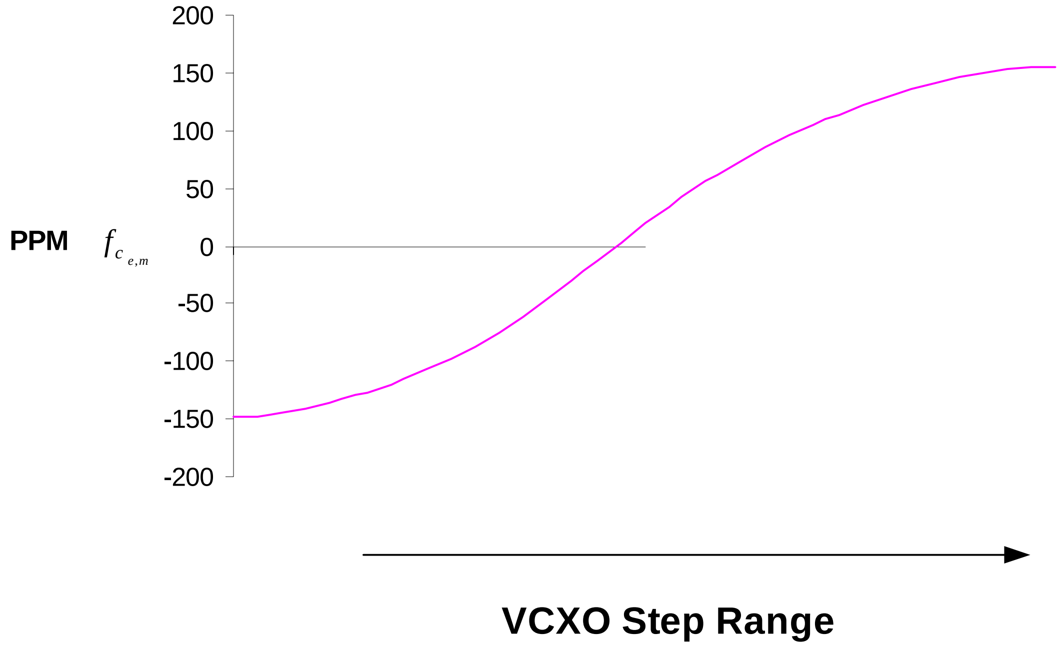


Figure 1 Predictable VCXO Response

Contrast this to figure 2 where a VCXO appears to function correctly and then mysteriously begins to function in a non-monotonic fashion. In this example the probability for failure is high since the nominal frequency is most likely to be exercised during normal operation. A non-monotonic response can mislead the feedback system resulting in loss of lock. Also shown is deviant behavior towards the upper end of the pull curve. This abrupt frequency transition can cause temporary loss of lock. Too often, engineers will tend to compromise a bad response based on magnitude of deviation, location and rate-of-change of frequency. *All* compromises can be dangerous. Now that we have identified pull curve problems, we are ready to delve into the mystery. Doing so requires that we perform a background check to ensure that oscillator fundaments are in place.

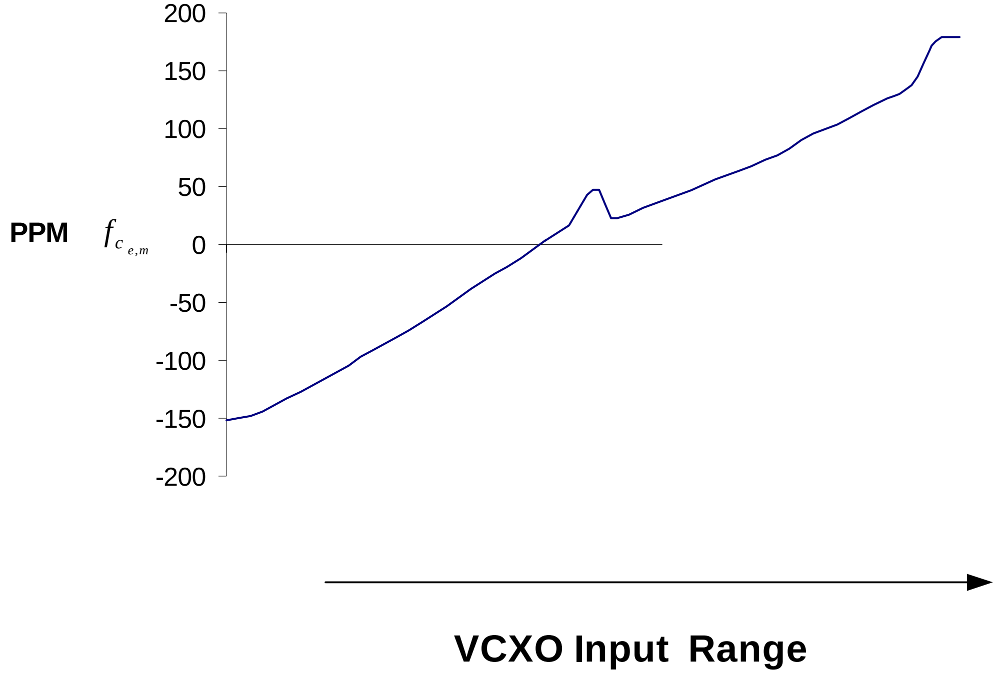


Figure 2 Non-Monotonic VCXO Behavior

Oscillator Review

From a simplistic standpoint, when an output logic amplifier produces a saturated, non-linear square-wave output, what is said about the gain? Your initial conclusion is that there is *sufficient* gain and you are correct. We will tackle excess gain shortly. The network of which we refer is most likely composed of the ubiquitous inverter found on practically every logic system design known as the Pierce configuration. High gain and wide bandwidth are the trademarks so multiple applications and various environments will work. With square waves banging away on the output, harmonic energy is present. For clarification, we introduce *electrical* harmonics.

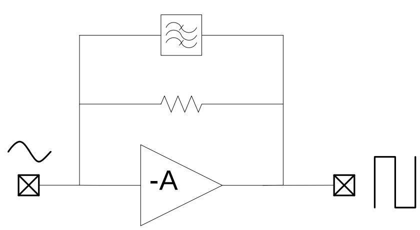


Figure 3 Non-linear Amplifier

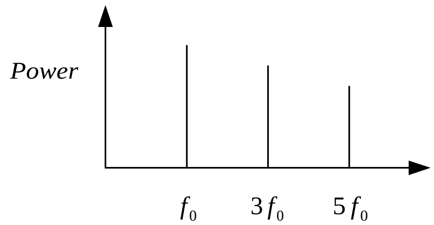


Figure 4 Multiple Tone Generation due to Square Wave

Electrical harmonics are harmonics specifically generated by the active gain element. Most notable are presence of strong 3rd and 5TH harmonics indicative of square wave behavior. Referring to figure 3, note the placement of an ideal Band Pass Filter (BPF) in the feedback path, screening all but the fundamental tone to arrive back at the input. Now imagine an *additional* BPF centered at the electrical 3rd harmonic. Could both the fundamental and 3rd simultaneously satisfy Barkhausen and oscillate? The simple answer is yes as long as the amplifier and feedback can support the necessary gain and phase for such operation. The crystal element behaves in much the same way as multiple BPF filters, ready to pass energy from input to output if energy is present for doing so.

Good oscillator design ensures that the correct mode of operation is encouraged while *discouraging* other modes of operation such as overtone excitation. A common misconception is that many engineers assume that overtone or other modes of operation can never happen because there is no mention in the datasheet. In response I ask the question as to where in the crystal datasheet does it say that it *cannot* run in overtone operation? Most crystal datasheets guarantee operation in *one* mode given a set of loading conditions and rarely mention anything else.

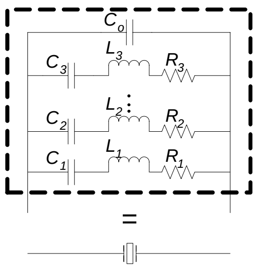
Crystal Overtone Discussion

A piezo element mathematical description is a complex multi-dimensional problem not easily resolved. In discussing harmonics earlier in this discussion, I mentioned *electrical* harmonics as those generated from the non-linearity of the amplifier. This is important in order to set the stage for another set of harmonic excitation modes naturally present in the piezoelectric material. Excitation of the crystalline structure at frequencies approximately 3, 5, 7 (etc) times that of the fundamental results in what we will call *mechanical* harmonic, or *mechanical overtone* modes. Clear distinction between electrical tones (generated by the amplifier) and mechanical modes (subject to excitation of passing energy) are necessary. The key to understanding is that VCXO frequency transition problems are often the cause of electrical and mechanical mode coupling; therefore we need to better understand *how* to avoided this scenario.

A little known fact is that mechanical overtone properties of the crystal do not necessary align with the electrical overtone ratios. This is largely because finite plate mechanical vibrating systems are not perfect. Placement of the 3rd harmonic with respect to (w.r.t.) the fundamental can be specified through design of the crystal blank and electrode size. *Why* we want to do this will soon become apparent.

Crystal Electrical Model

From an electrical standpoint, figure 5 outlines a common electrical model. Capacitor C_0 specifies the intrinsic capacitance as generated between the crystal plates known as static capacitance. C_1, L_1 and R_1 are representative of the *fundamental* motional leg of the crystal internal network. Two additional motional legs in figure 5 cover the 3rd and 5th overtones. Associated with each motional capacitor is a motional inductive element. We use the term *motional* to distinguish between intrinsic vs. real components.



$$C_1 = 0.1 \rightarrow 0.001\text{pf}$$
$$R_n = R_1 N^2$$
$$C_n = \frac{C_1}{N^2}$$
$$L_n = L_1$$

Figure 5 Crystal Electrical Equivalent

A careful review of the motional capacitance, inductance and resistance models leads to some fascinating relationships. The motional capacitance for the fundamental ranges from approximately 0.1 to 0.001pF, but generally favors the low side (<30fF). This is small when you think about it, but the motional capacitances for the mechanical harmonics reduce by a factor of $1/N^2$ for each overtone excitation mode. Yet, the motional inductance for every motional leg is always the same. The resistance increases by N^2 for each higher harmonic so it should be obvious that if given the choice, the expected mode of operation is the least resistive route, as the 3rd mechanical harmonic will theoretically produce a resistance 9 times greater when compared with the fundamental mode.

Crystal Pierce Oscillator Topology

Our attention now turns to the ubiquitous Pierce oscillator, why a Pierce configuration? My speculation is that two-pin inverting elements represent logic buffers in use by logic designers.

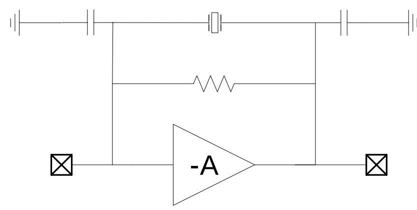


Figure 6 Ubiquitous Pierce Oscillator Network Configuration

Figure 6 should start to look familiar. The filter presented earlier is replaced by a filter structure called a crystal. Besides this, the only other difference is in the addition of the loading capacitors, C_L on each crystal leg. As a reference point, the crystal, in conjunction with the shunt capacitors forms a "tank" circuit implementation. Will this network oscillate? Most everyone will raise their hands and say yes because most of us know by experience that it should oscillate. After all, this is not new material! Nevertheless, why should it oscillate? The fact is that oscillation(s) will only occur at frequency point(s) where the network meets the Barkhausen criteria; a balancing act of phase and gain that produces an output frequency. While we take the *simplicity* of network design for granted, the real fact is that there are many motional reactive elements bundled into the crystal of which any one, or a combination can resonate.

The purpose of the loading capacitors is to perform two main functions. First, load the crystal for parallel load operation (meet the datasheet spec). Second, by adding shunt capacitors, this creates the condition where we end up creating a positive crystal phase change. We are not talking about large amount of phase simply because of the crystal Q. With a steep curve, it does not take much "C" to make a frequency change.

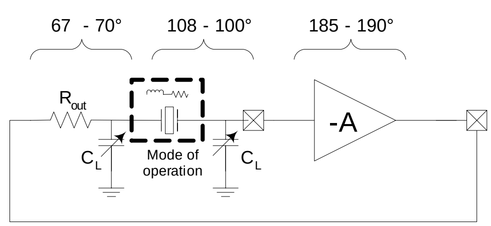


Figure 7 Pierce Configuration with Adjustable Shunt Capacitors

Moving off the common textbook discussion, figure 7 gives a reality check on phasing when we consider a functioning Pierce VCXO configuration. Note that the fixed load caps are now adjustable. Changing the values of the shunt capacitance ends up changing the phase through the network and modifying the load reactance. Simply stated, in order to maintain oscillation as a result to a change in phase, the output frequency *must* compensate, or change. If the system cannot, then Barkhausen requirements fail and oscillation dies.

This article should help the user understand core oscillator operating principles and the specifics on crystal operational modes. Through proper use of the concepts and principles discussed, better crystal specification and screening guides for stable VCXO operation may commence.

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