Introduction

The VCXO tuning procedure developed here has two applications. First, in the design phase as a means of selecting a crystal, that when paired with a given VCXO oscillator will yield a VCXO with sufficient pull range for the application. Second, once the selected crystal and oscillator are in the lab and a sample characterized crystal is obtained, the procedure can be used to directly tune the VCXO center frequency with a minimum number of tuning capacitor iterations.

Tuning a VCXO is not as straightforward as tuning a clock generator; a VCXO is not tuned for a single frequency. A VCXO is tuned when the magnitude of the positive pull range from the VCXO center frequency is the same as the magnitude of the negative pull range. But the magnitude of the pull range is not known before hand. Further, the non-linearity of the load curve means that the tuning capacitor that centers the VCXO pull range is not that capacity, when added to the average of the maximum and minimum varactor capacities and all the parasitic capacities, equals the crystal load capacity.

Using the Load Curve to Tune a VCXO

For the purposes of crystal selection and tuning, two sets of information are required. The crystal circuit element values C0, C1, and CLn, and the load curve[1] are shown in Equation 1. CLn is the nominal parallel load capacity that tunes the crystal parallel resonance to the crystal center frequency, FL. In standard usage, this is CL but here the n suffix is added because in the derivation that follows, CL is varied plus or minus about the nominal value of CL.

Also required are the values of the VCXO oscillator's voltage variable capacitors when the control voltage is set to the maximum and minimum values, C_{VH} and C_{VL}. CLn is subtracted from each of these two capacities to form ΔC_{VH} and ΔC_{VL}, which define the largest decrease in the load capacity from CLn and the largest increase in load capacity from CLn respectively. These two deviations in turn describe the range of frequency offsets, ΔFL/FL, from the crystal center frequency when loaded by the varactor capacity across all VXO control voltages.

This information allows the tuning capacitor that centers the VCXO pull range about FL and the positive and negative tuning range to be calculated directly as will be shown below. Note that the fractional frequency offsets have not been converted to ppm; ΔFL and FL are in Hz. The normalization of all capacities by Y=C0+CLn simplifies the tuning derivation that follows.

Equation 1

$$\frac{\Delta F_L}{F_L} = -\frac{1}{2}\frac{C1}{Y}\frac{\frac{\Delta CL}{Y}}{\left(1+\frac{\Delta CL}{Y}\right)}$$

where
$Y = C0 + CLn$

The polarity of the voltage transfer curve of the VCXO is not relevant to the tune procedure. It is immaterial whether the maximum and minimum control voltages correspond to the maximum and minimum VCXO frequencies or vice versa. Further, the varactor capacities being used are the equivalent parallel varactor capacities across the crystal terminals. The varactor capacitors are typically implemented as two shunt capacitors to ground, one on the VCXO oscillator input and on the oscillator output. If these capacitors are provided by the oscillator manufacturer ground referenced, simply divide the values by two to obtain the parallel values of ΔC_{VH} and ΔC_{VL}.

First solve Equation 1 for the normalized parallel load capacity across the crystal for a given ΔFL/FL.

Equation 2

$$\frac{\Delta CL}{Y} = 2\frac{\frac{Y}{C1}\frac{\Delta F_L}{F_L}}{1+\frac{Y}{C1}\frac{\Delta F_L}{F_L}}$$

[1] IDT Application Note AN-831, “The Crystal Load Curve”

Equation 2 is used is used to determine the normalized values of ΔCVH and ΔCVL in terms of the fractional offset frequency errors measured when the control voltage is at the maximum and minimum value respectively in Equation 3 and Equation 4.

$$\frac{\Delta CL_{VH}}{Y} = \frac{\Delta C_{VH}}{Y} = 2\frac{\frac{Y}{C1}\left[\frac{\Delta F_L}{F_L}\right]_{VH}}{1+\frac{Y}{C1}\left[\frac{\Delta F_L}{F_L}\right]_{VH}}$$

Equation 3

$$\frac{\Delta CL_{VL}}{Y} = \frac{\Delta C_{VL}}{Y} = 2\frac{\frac{Y}{C1}\left[\frac{\Delta F_L}{F_L}\right]_{VL}}{1+\frac{Y}{C1}\left[\frac{\Delta F_L}{F_L}\right]_{VL}}$$

Equation 4

The condition to determine CTC, the parallel tuning capacitor, is that the algebraic sum of the fractional frequency offsets generated is zero when the control voltage of the VCXO is at the maximum and minimum and the tuning capacitor have been added to the crystal load. This condition is shown in Equation 5 below. When the magnitude of the corresponding frequency offsets, [ΔFL/FL]Tuned+ and [ΔFL/FL]Tuned-, at the maximum and minimum control voltage are equal, the center frequency of the oscillator will also be at the nominal frequency.

$$\left[\frac{\Delta F_L}{F_L}\right]_{Tuned+} + \left[\frac{\Delta F_L}{F_L}\right]_{Tuned-} = -\frac{1}{2}\frac{C1}{Y}\left(\frac{\frac{\Delta C_{VH}+C_{TC}}{Y}}{1+\frac{\Delta C_{VH}+C_{TC}}{Y}}\right) - \frac{1}{2}\frac{C1}{Y}\left(\frac{\frac{\Delta C_{VL}+C_{TC}}{Y}}{1+\frac{\Delta C_{VL}+C_{TC}}{Y}}\right)$$
$$= 0$$

Equation 5

Rearranging results in a quadratic in CTC.

$$0 = \frac{\Delta C_{VH}+C_{TC}}{\left(1+\frac{\Delta C_{VH}+C_{TC}}{Y}\right)} + \frac{\Delta C_{VL}+C_{TC}}{\left(1+\frac{\Delta C_{VL}+C_{TC}}{Y}\right)}$$
$$= \left(\Delta C_{VH}+C_{TC}\right)\left(Y+\Delta C_{VL}+C_{TC}\right)+\left(\Delta C_{VL}+C_{TC}\right)\left(Y+\Delta C_{VH}+C_{TC}\right)$$
$$= Y\left(\Delta C_{VH}+\Delta C_{VL}\right)+2Y\,C_{TC}+2\left(\Delta C_{VH}+C_{TC}\right)\left(\Delta C_{VL}+C_{TC}\right)$$

$$0 = Y\left(\Delta C_{VH}+\Delta C_{VL}\right)+2\Delta C_{VH}\,\Delta C_{VL}+2\left(Y+\Delta C_{VH}+\Delta C_{VL}\right)C_{TC}+2{C_{TC}}^2$$

Equation 6

Equation 6 can be solved for both roots, but the most positive square root is the physically meaningful solution. This can be checked by substitution back into the load curve, Equation 1.

Since the most positive root is C_{TC}, solving the quadratic can be done directly.

$$C_{TC} = -\left(\frac{Y+\Delta C_{VH}+\Delta C_{VL}}{2}\right)+\sqrt{\left(\frac{Y+\Delta C_{VH}+\Delta C_{VL}}{2}\right)^2-\frac{Y}{2}\left(\Delta C_{VH}+\Delta C_{VL}\right)-\Delta C_{VH}\,\Delta C_{VL}}$$

$$= \frac{Y}{2}\left[-\left(1+\frac{\Delta C_{VH}}{Y}+\frac{\Delta C_{VL}}{Y}\right)+\sqrt{\left(1+\frac{\Delta C_{VH}}{Y}+\frac{\Delta C_{VL}}{Y}\right)^2-2\left(\frac{\Delta C_{VH}}{Y}+\frac{\Delta C_{VL}}{Y}\right)-4\frac{\Delta C_{VH}}{Y}\frac{\Delta C_{VL}}{Y}}\right]$$

$$= \frac{Y}{2}\left[-\left(1+\frac{\Delta C_{VH}}{Y}+\frac{\Delta C_{VL}}{Y}\right)+\sqrt{1+2\frac{\left(\Delta C_{VH}+\Delta C_{VL}\right)}{Y}+\left(\frac{\Delta C_{VH}}{Y}+\frac{\Delta C_{VL}}{Y}\right)^2-2\frac{\left(\Delta C_{VH}+\Delta C_{VL}\right)}{Y}-4\frac{\Delta C_{VH}\,\Delta C_{VL}}{Y^2}}\right]$$

$$= \frac{Y}{2}\left[-\left(1+\frac{\Delta C_{VH}}{Y}+\frac{\Delta C_{VL}}{Y}\right)+\sqrt{1+\left(\frac{\Delta C_{VH}}{Y}\right)^2+2\frac{\Delta C_{VH}\,\Delta C_{VL}}{Y^2}+\left(\frac{\Delta C_{VL}}{Y}\right)^2-4\frac{\Delta C_{VH}\,\Delta C_{VL}}{Y^2}}\right]$$

$$= \frac{Y}{2}\left[\sqrt{1-2\frac{\Delta C_{VH}\Delta C_{VL}}{Y^2}+\left(\frac{\Delta C_{VH}}{Y}\right)^2+\left(\frac{\Delta C_{VL}}{Y}\right)^2}-\left(1+\frac{\Delta C_{VH}+\Delta C_{VL}}{Y}\right)\right]$$

$$= \frac{1}{2}\left[\sqrt{Y^2+\left(\Delta C_{VL}-\Delta C_{VH}\right)^2}-\left(Y+\Delta C_{VH}+\Delta C_{VL}\right)\right]$$

Substituting for Y and removing the CLn offset in the capacities results in a simpler form in terms of physical circuit capacities.

$$C_{TC} = \frac{1}{2}\left[\sqrt{Y^2+\left(\Delta C_{VL}-\Delta C_{VH}\right)^2}-\left(Y+\Delta C_{VH}+\Delta C_{VL}\right)\right]$$

$$= \frac{1}{2}\left[\sqrt{\left(C0+CLn\right)^2+\left(\left(C_{VL}-CLn\right)-\left(C_{VH}-CLn\right)\right)^2}-\left(C0+CLn+C_{VH}-CLn+\Delta C_{VL}-CLn\right)\right]$$

$$C_{TC} = \frac{1}{2}\left[\sqrt{\left(C0+CLn\right)^2+\left(C_{VL}-C_{VH}\right)^2}-\left(C0+C_{VH}+\Delta C_{VL}-CLn\right)\right] \qquad \textbf{Equation 7}$$

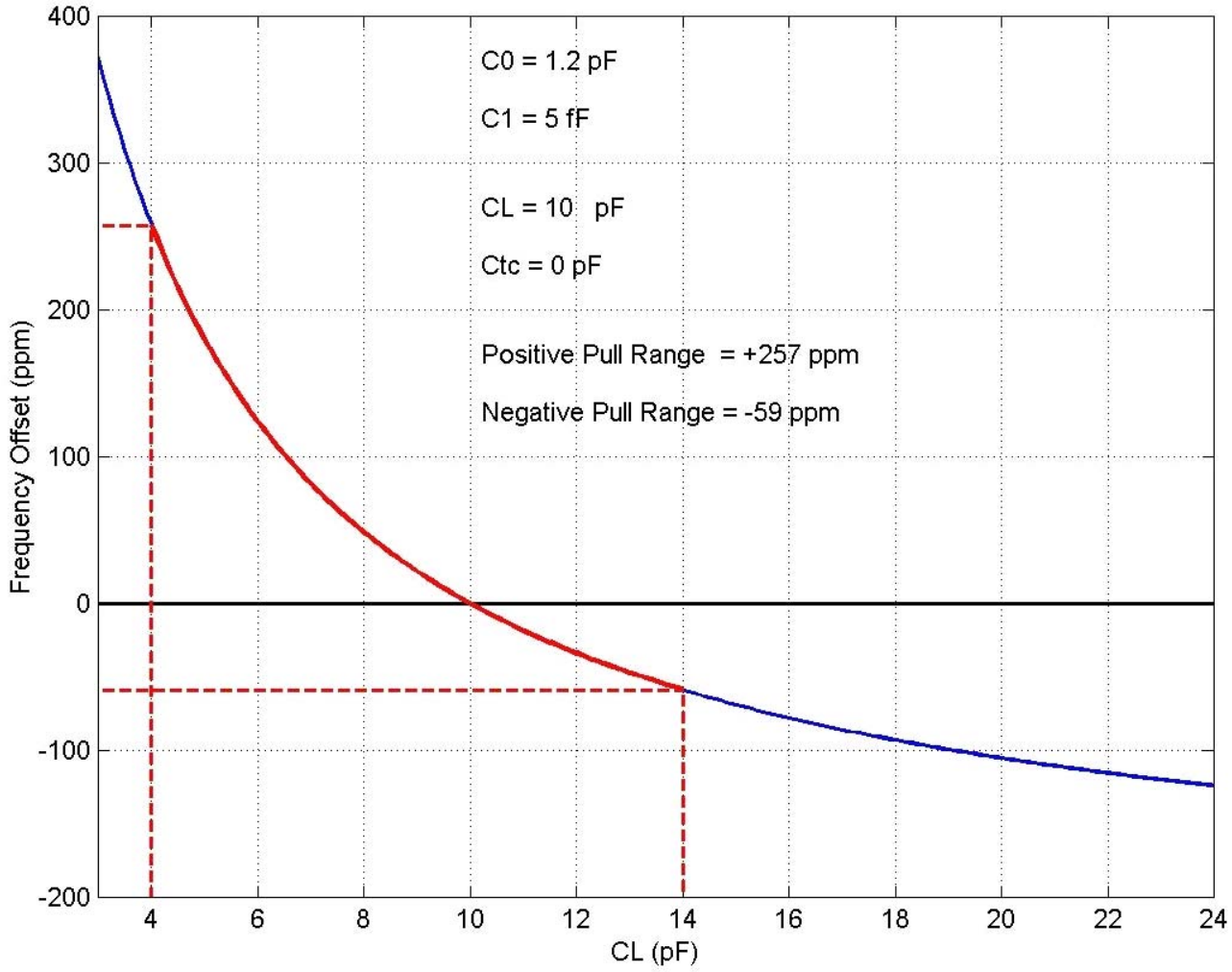
Typically the value of C_{TC} is positive and indicates that the VCXO can be tuned to the center frequency. A negative tuning capacity indicates one of three things:

1. The amount of capacity that must be removed from the PCB in a new board layout if the crystal is to be retained.
2. The amount by the previous tune capacitor was too large.
3. The minimum amount by which the load capacity of the crystal must increased to yield a tunable VCXO. The value of this additional capacity is used to specify a new crystal that can be tuned and used with the existing circuit board.

Example Tune

The steps of the tune procedure are illustrated with a simple hypothetical case of a VCXO and PCB layout with no tuning cap added. The pre-tune characteristics of the VCXO are shown in Figure 1 below; ΔC_{VL} = 14pF, C_{VH} = 4pF and therefore ΔC_{VL} = +4pF, ΔC_{VH} = -6pF.

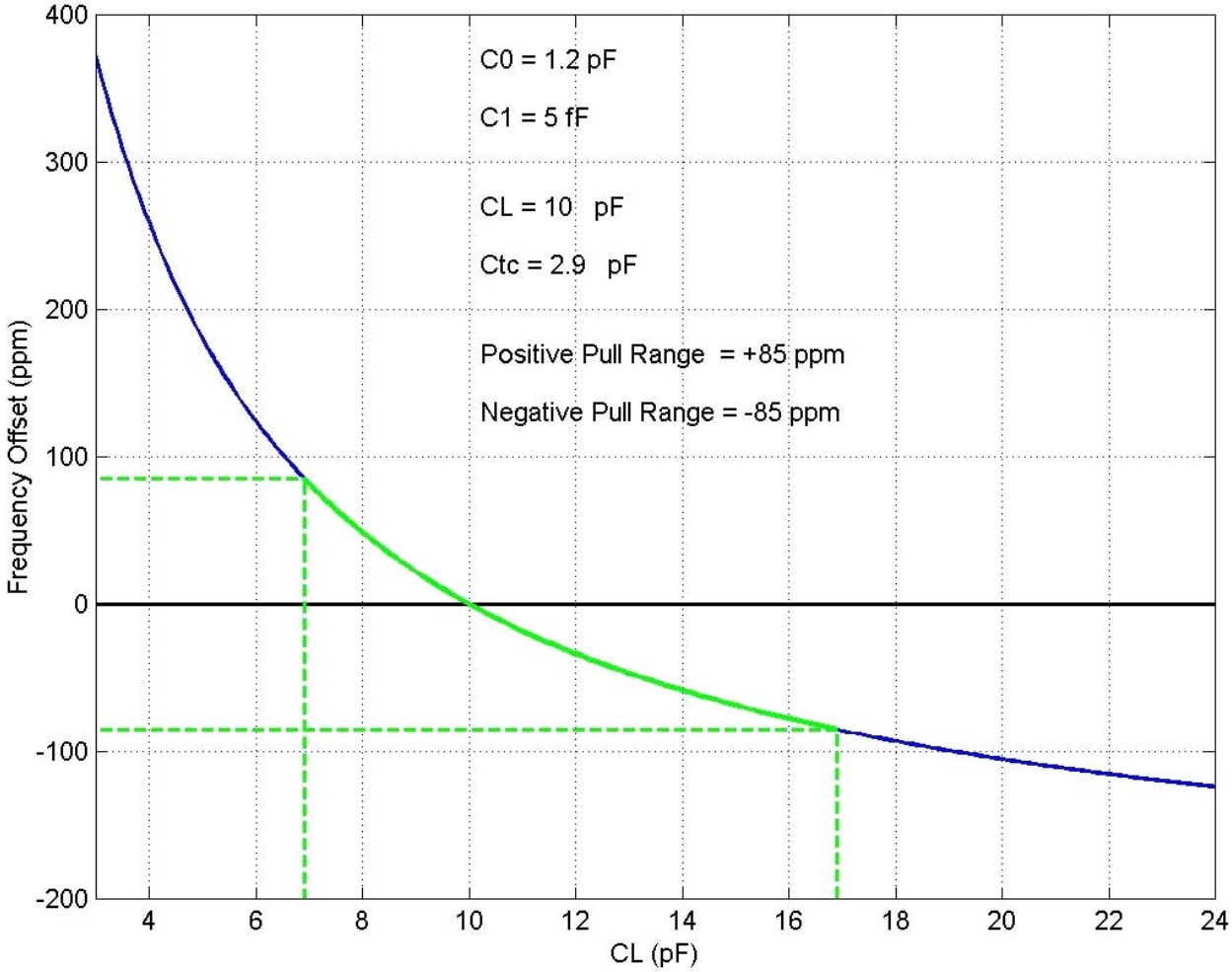
Figure 1. Pre-Trim VCXO Pull Range Example



The value of C_{TC} calculated from Equation 7 is 2.9pF. This value has been added across the crystal leads to center the pull range of the VCXO. The final pull range is shown in Figure 2 where three things can be noted.

1. The change in C_L remains the same; the change in the capacity of the varactor capacitors is unaffected by the addition of the fixed C_{TC} capacity.
2. The reduction in positive pull range is much larger than the gain in negative pull range; a consequence of the non-linearity of the pull curve.
3. The pull range of the VCXO is centered at C_L=10pF.

Figure 2. Post-Trim VCXO Pull Range Example



If this example was for a characterized crystal and an oscillator in the lab, the value of C_{TC} is to be applied to the VCXO. This is accomplished with two tuning capacitors; one applied at the crystal lead connected to the oscillator input and ground and the other applied at the crystal lead connected to the oscillator output and ground. The value of these two new capacitors is twice that of C_{TC}. The doubling comes about because the AC waveforms across the crystal are 180° out of phase. Since the current through each grounded tuning capacitor is the same, the two capacitors can equivalently be placed in series across the crystal leads. The parallel equivalent capacity is then half that of the two grounded capacitors.

Revision History

Rev.	Date	Originator	Description of Change
A	05/12/14	–	Initial release.
B	09/23/14	P. Wissell	1. Added text to section “Using the Load Curve to Tune a VCXO” to eliminate the need to consult AN-831 for some nomenclature definitions. 2. Simplified Equation 7.

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