# The Impact of Tuning Circuit Configuration on the Start-up Time of Crystal Oscillators

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**Abstract**

*It is understood that a crystal oscillator does not generate a periodic signal at the instant power is applied to the circuit. Start-up time is affected by many factors as explained in various literature. In this paper, it is shown that start-up time can be a function of the arrangement of frequency determining components within the oscillator loop. The reason for the resulting change in loop gain is not necessarily obvious. Frequency tuning elements are known to influence the effective series resistance within the loop, so it is necessary that they be included in open loop gain and negative resistance analyses. Empirical results and circuit simulations provide insight into the observed behavior. Variations of the Colpitts oscillator as well as other oscillator circuit topologies are examined for this phenomenon.*

## I. Introduction

Start-up refers to the time that is required for an oscillator to sustain a usable output at the desired frequency. Regardless of whether the oscillator trigger mechanism is noise or circuit ringing, the start-up of crystal controlled oscillators is influenced by many factors such as loop gain, resonator Q, circuit loading and temperature.

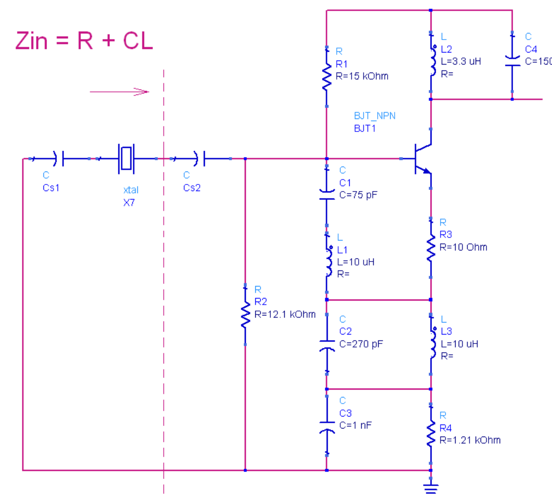
Tsuzuki presented a formula to model the start-up of oscillators; however, the impact of the tuning circuitry is not taken into account [1]. It will be demonstrated that consideration must be given to the circuit's effective series resistance (ESR), the circuit's negative resistance and certain stray capacitances to properly analyze the start-up.

The ESR within an oscillator loop is a function of the resonator motional resistance R1, static capacitance C0 and load capacitance $C_L$ as given in Equation 1 [2].

$$ESR = R_1 \times \left( \frac{C_O + C_L}{C_L} \right)^2 \qquad \textbf{Equation 1}$$

According to this equation the ESR decreases with increasing load capacitance, and vice versa. This change is likely to be observed as variation in output amplitude as the oscillator frequency is adjusted. $C_L$ may sweep from 10 pF to 40 pF in oscillators designed with mechanical or electronic frequency control (EFC). Adjustment of frequency at the manufacturer's set-up will shift the range up or down.

The negative resistance available at Zin in Schematic 1 is an indicator of the excess loop gain. Designers have their own opinions as to how large this resistance should be relative to the resonator resistance. Certainly the magnitude of the negative resistance must be greater than the collective circuit losses and resonator resistance for oscillations to be sustained.




**Schematic 1:** Colpitts oscillator input impedance

A 5 MHz Colpitts oscillator with Cs2 included as a means for adjusting frequency is considered. Simulation of the impedance Zin (Cs1 open) establishes that the available negative resistance decreases as $C_L$ decreases (Figure 1). Oscillations cannot be sustained for very low $C_L$ since the input resistance becomes positive or of too little negative resistance.

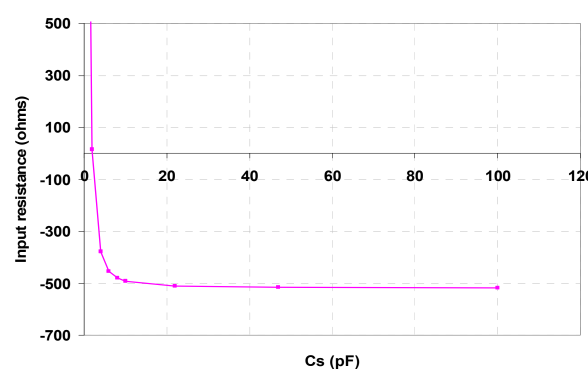



**Figure 1:** Input resistance vs. Cs

## II. Tuning Circuit Impact on Start-up Time

Empirical evidence shows that component arrangement within the tuning circuit has a direct impact on oscillator start-up as well as loop gain. The measured start-up envelope of the 5 MHz oscillator mentioned previously with Cs1 = 10 pF and Cs2 shorted is shown in the following plot.

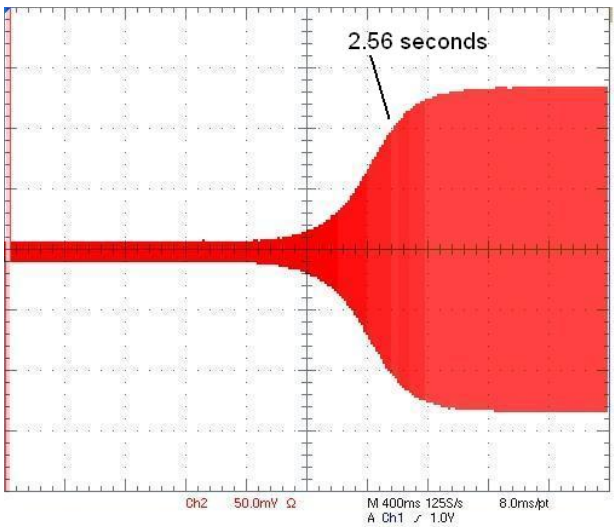



**Figure 2:** Measured start-up with Cs1 = 10 pF, Cs2 = short

Swapping the values of Cs1 and Cs2 increases the start-up time by 320 ms (12.5%) as shown in Figure 3.

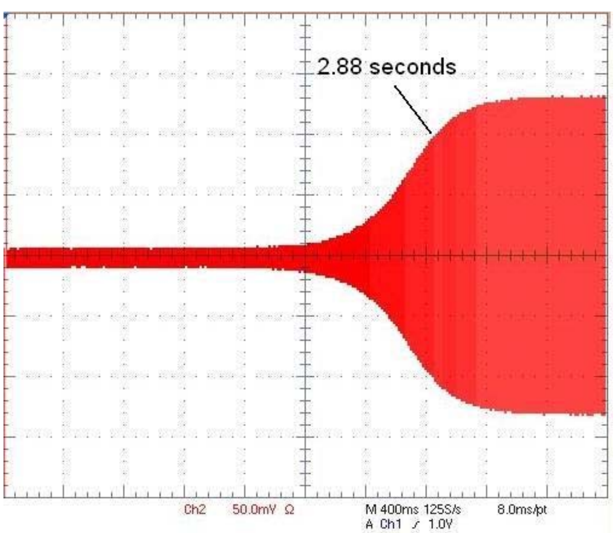



**Figure 3:** Measured start-up with Cs2 = 10 pF, Cs1 = short

## III. Explanation for Observed Behavior

The four element model which follows is commonly used to represent a quartz resonator. Capacitance C0 is the parallel combination of the electrode-to-electrode and electrode-to-enclosure capacitances.

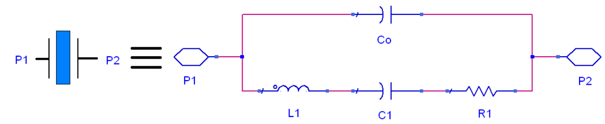



**Figure 4:** Four element quartz resonator model

C0 can be separated into its constituent capacitances yielding a more comprehensive resonator model shown in Figure 5. Elements Cd1 and Cd2 represent the capacitances between each of the electrodes and the resonator enclosure, while C10 is the electrode-to-electrode capacitance. Parzen mentioned that the presence of Cd1 and Cd2 will influence the resonator's behavior [3]. It will be shown that these are significant capacitances relative to C10, and play an important role in oscillator behavior.

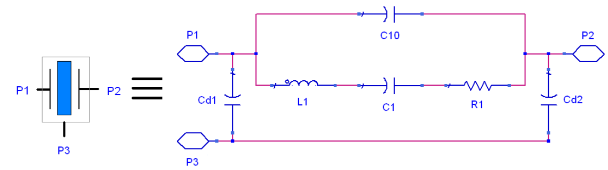



**Figure 5:** Six element quartz resonator model

## IV. Capacitance of Quartz Resonator Enclosures

Table 1 summarizes the measured electrode and enclosure capacitances for various quartz resonator and package designs. Measurements are obtained using a handheld capacitance meter operating at a relatively low frequency. Enclosure and electrode capacitances are numerically derived from the raw data.

| DUT | C10 (pF) | Cd1 (pF) | Cd2 (pF) |
|---|---|---|---|
| 1 | 1.4 | 1 | 1 |
| 2 | 1.7 | 1.4 | 1.15 |
| 3 | 2.15 | 1.5 | 1.45 |
| 4 | 2.55 | 1.15 | 1.15 |
| 5 | 2.65 | 1.15 | 1.15 |
| 6 | 2.0 | 3.2 | 2.95 |
| 7 | 3.2 | 1.1 | 1.1 |
| 8 | 2.45 | 1.15 | 0.95 |
| 9 | 2.62 | 1 | 1 |
| 10 | 1.7 | 0.6 | 0.6 |

**Table 1:** Resonator enclosure and electrode capacitances

| | | | | | |
|---|---|---|---|---|---|
| DUT 1: | 5 MHz | fund | AT | HC-46/U | 0.174 inches depth |
| DUT 2: | 5 MHz | 3rd | SC | HC-37/U | 0.200 inches height |
| DUT 3: | 5 MHz | 3rd | SC | HC-40/U | 0.335 inches height |
| DUT 4: | 10 MHz | 3rd | SC | HC-37/U | 0.200 inches height |
| DUT 5: | 10 MHz | 3rd | SC | HC-37/U | 0.155 inches height |
| DUT 6: | 10 MHz | 3rd | SC | HC-40/U | 0.250 inches height |
| DUT 7: | 10 MHz | 3rd | SC | HC-37/U | 0.265 inches height |
| DUT 8: | 13 MHz | 3rd | SC | HC-43/U | 0.135 inches depth |
| DUT 9: | 25 MHz | 3rd | AT | HC-37/U | 0.235 inches height |
| DUT 10: | 100 MHz | 3rd | SC | HC-35/U | 0.200 inches height |

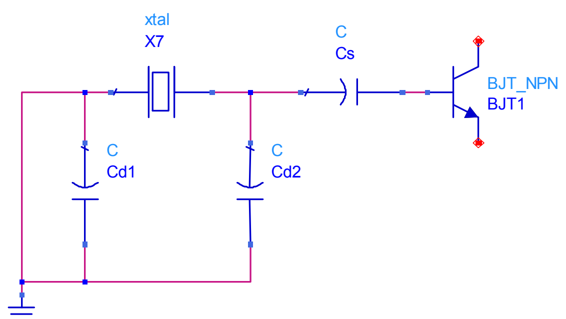
The majority of these devices have similar enclosure capacitances. As demonstrated by DUT10, higher frequency resonators tend to have smaller Cd1 and Cd2 due to smaller electrode diameters. DUT6 utilizes a quad-relief mounting structure that increases the effective electrode surface area relative to the enclosure thus increasing Cd1 and Cd2.

## V. Simulated Loop Gain and Negative Resistance

Simulations presented in this paper are performed using Advanced Design System (ADS) from Agilent EEsof [4].

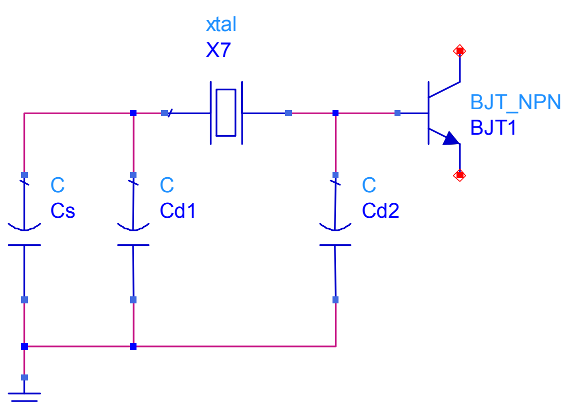
A Colpitts oscillator that includes Cd1 and Cd2 is considered in this section. A 5 MHz quartz resonator with motional capacitance C1 = 1 fF, motional resistance R1 = 40 Ω and C10 = 2.5 pF controls the frequency.

Suppose the designer chose to place a 10 pF capacitor (Cs) between the resonator and transistor base as in Schematic 2. This configuration effectively short circuits Cd1. The magnitude of the open loop gain at the zero-phase frequency is 1.118395.




**Schematic 2:** Cs = 10 pF in arrangement 1

Now, suppose that the designer had placed the 10 pF capacitor between the resonator and ground as shown in the following schematic. Enclosure capacitance Cd1 is now in parallel with Cs. The magnitude of the gain increases to 1.120882.




**Schematic 3:** Cs = 10 pF in arrangement 2

If Cd1 and Cd2 are omitted from the analysis then the loop gain is 1.121027, irrespective of the placement of Cs.

A rigorous analysis of the negative resistance for Schematic 1, therefore, requires the addition of Cd2 from Zin to ground. With Cs2 = 10 pF (Cs1 open), the calculated real part of the impedance if Cd2 = 1 pF is -398 Ω while the resistance with Cd2 omitted is -492 Ω. The corresponding open loop gain magnitudes are 1.118395 and 1.120055, respectively.

In the circuit, Cd2 causes a substantial decrease in the magnitude of the negative resistance at Zin. Therefore, placing a resonator in the circuit guarantees a reduction of the available negative resistance. It is apparent in Figure 6 that the difference between the negative resistances with Cd2 = 1 pF and with Cd2 open increases with decreasing Cs2. Per Figure 7, the negative resistance change at low $C_L$ is more sensitive to the magnitude of Cd2.

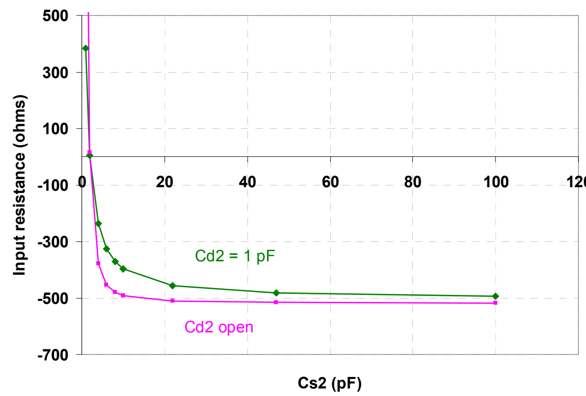



**Figure 6:** Input resistance versus Cs2

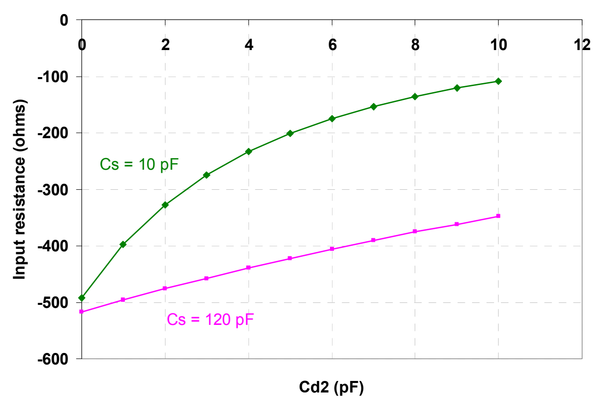



**Figure 7:** Input resistance versus Cd2

## VI. Simulated Start-up Response

Computer speeds and simulation engines have matured to the point that the start-up response of high-Q oscillators can be computed in a relatively short period of time. Transient simulations of oscillators with unloaded Q's of 800K completed in less than thirty minutes using a 2 GHz processor. Simulated, but not included in this report, is a two-million $Q_{unloaded}$ oscillator that took just one hour to generate 300 milliseconds of transient analysis data. During the simulations, a stepped voltage starts the ringing that grows to sustained oscillations. A low amplitude sinusoidal source in the oscillator loop can be used as an alternate method to excite the desired oscillation.

The examples in this section use a 5 MHz quartz resonator with C1 = 1 fF, R1 = 40 Ω and C10 = 2.5 pF. The start-up response in Figure 8 represents the oscillator configuration of Schematic 3 with Cs = 10 pF and Cd1 = Cd2 = 1 pF. The time to reach 200 $mV^+$ is 95 milliseconds.

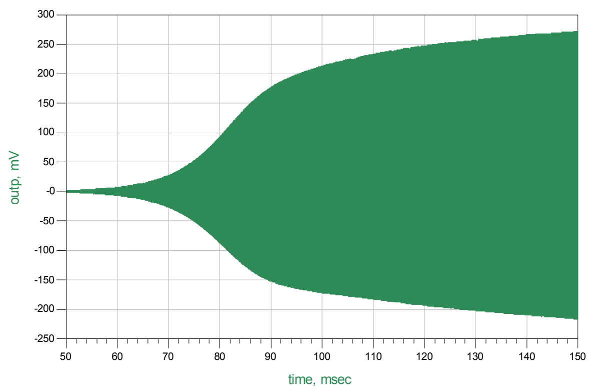



**Figure 8:** Simulated start-up of Schematic 3

Moving Cs to the other side of the resonator increases start-up to 121 milliseconds as shown in Figure 9. The resulting start-up difference of the two arrangements is 26 milliseconds. The simulated start-up of both configurations as a function of Cs is plotted in Figure 10.

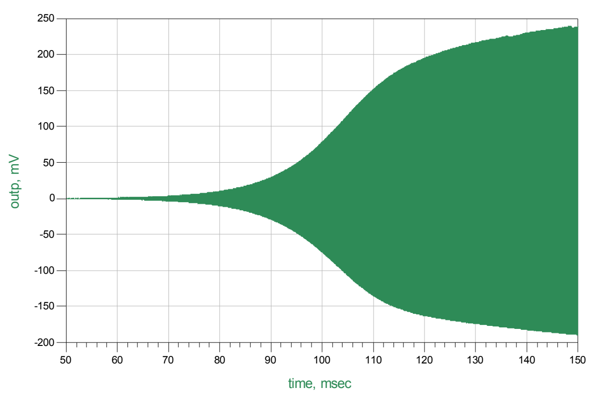



**Figure 9:** Simulated start-up of Schematic 2

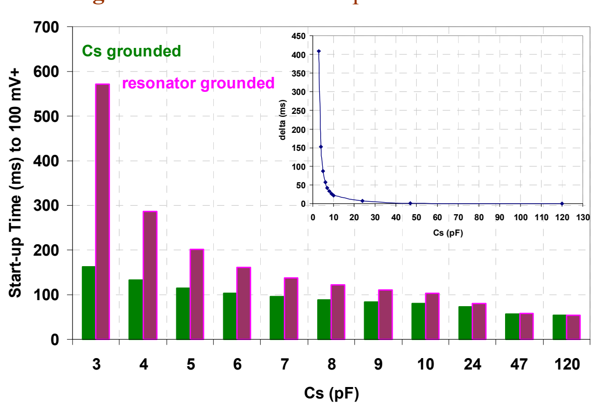



**Figure 10:** Start-up versus Cs

The simulated start-up of both circuits as a function of Cd2 with Cs = 10 pF is plotted in Figure 11. It is clear that Cd2 impacts the start-up despite the circuit arrangement, but much more so when the resonator is grounded. The enclosure capacitances, therefore, are crucial elements in the determination of the loop gain.

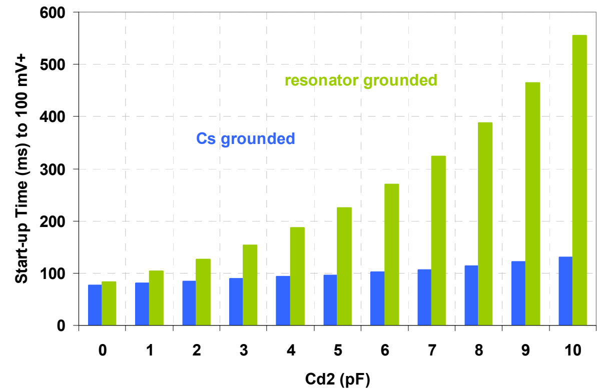
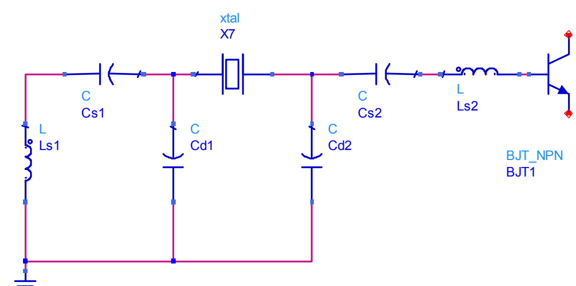



**Figure 11:** Start-up versus Cs2

Oscillator tuning circuits often include an inductor to achieve the necessary load capacitance, particularly when varactors are included in the loop. The simulated start-up of four arrangements of Schematic 4 are tabulated in Table 2. Cd1 and Cd2 are both 1 pF while the active circuit presents a capacitance of 80 pF.




**Schematic 4:** Tuning circuit with inductor and capacitor

| Ls1 (µH) | Ls2 (µH) | Cs1 (pF) | Cs2 (pF) | $C_L$ (pF) | Start-up time (ms) |
|---|---|---|---|---|---|
| 18 | short | 10 | short | 11.32 | 80 |
| 18 | short | short | 10 | 12.04 | 104 |
| short | 18 | 10 | short | 11.68 | 76 |
| short | 18 | short | 10 | 11.56 | 99 |

**Table 2:** Start-up for inductor-capacitor tuning circuit

Without exception, the quickest start-up time is achieved with Cs located between the resonator and ground. Notice that the configuration with the highest $C_L$ also has the slowest start-up time. So, the decrease in the ESR afforded by the increase in $C_L$ is eclipsed by the consequences of Cd1 and Cd2.

The arrangement effect is less noticeable at higher load capacitances. With Cs increased to 47 pF, the difference in start-up between the two arrangements is about two milliseconds as shown in Figure 12.

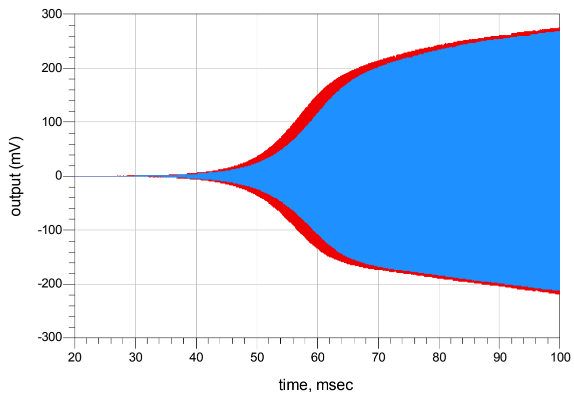



**Figure 12:** Cs = 47 pF, red is Schematic 3, blue is Schematic 2

An additional analysis confirms that the simulated start-up of each configuration is identical when Cd1 and Cd2 are omitted from the simulation.

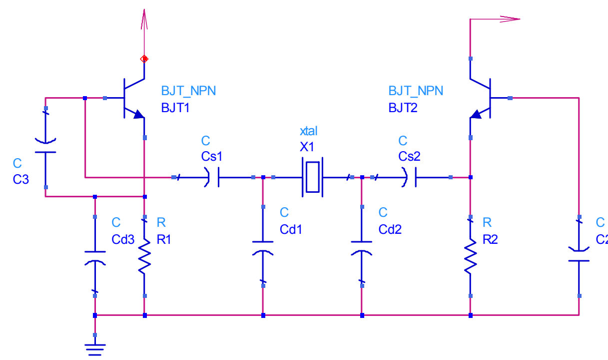
## VII. Frequency Dependency

The arrangement effect is observed in Colpitts oscillators operating between 5 MHz and 13 MHz. To determine the effect at higher frequencies, a 100 MHz Colpitts oscillator represented in Schematic 4 is tested. After multiple measurements with various tuning circuit arrangements, no difference in start-up could be detected. It is noted that the start-up varied by ± 1 millisecond between measurements of the same arrangement. It is possible that any actual variation may be buried in the measurement uncertainty.

Likewise, the simulations showed no discernible difference in start-up. With Ls1 = 0.33 µH, Cs1 = 10 pF, Cd1 = Cd2 = 0.6 pF and Cs2 = Ls2 = short, the simulated start-up of the circuit in Schematic 4 is 1.9 ms. A modification of the circuit with Ls1 = Cs1 = short, Ls2 = 0.33 µH and Cs2 = 10 pF resulted in no change of start-up. It was noted however, that simulations without Cd2 yielded a decrease of 0.45 milliseconds for the former arrangement and a 0.5 millisecond decrease for the latter.

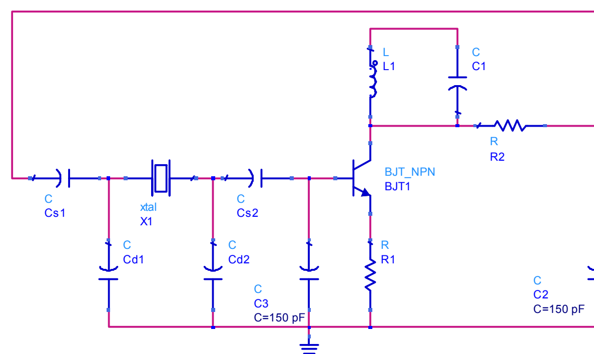
## VIII. Other Oscillator Configurations

Numerous variations of the Colpitts oscillator are possible. One common approach is to return the resonator to the emitter of a common base amplifier, which has a very low input resistance and reactance (Schematic 5). Breadboard results of this configuration at 13 MHz yielded a start-up range of 280 milliseconds to 600 milliseconds, depending upon the tuning circuit component arrangement.




**Schematic 5:** Colpitts with CB amplifier

The Pierce oscillator is another topology widely used in industry; a fragment of which is shown in Schematic 6. Breadboard results of a 5 MHz implementation indicate that the start-up time is unaffected by tuning circuit arrangement.




**Schematic 6:** Pierce Oscillator

Figure 13 shows the simulated start-up response with Cs1 = short and Cs2 = 10 pF overlaid with the simulated start-up condition Cs1 = 10 pF and Cs2 = short. The two responses are identical thus agreeing with the measurements obtained from the breadboard evaluation. It is likely that the relatively large capacitances of C2 and C3 damp-out the potential effects of Cd1 and Cd2.

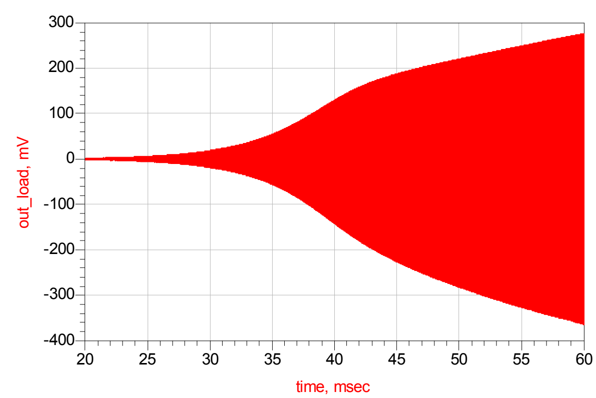
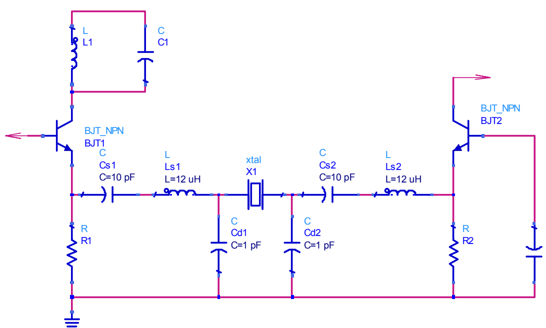



**Figure 13:** Pierce start-up response

The oscillator topology shown in Schematic 7 is sometimes utilized to achieve a low noise floor, and is similar to the "common base" Colpitts oscillator as one side of the resonator is terminated into a low impedance. In this example, a 10 MHz 3$^{rd}$ overtone SC resonator is used. The measured start-up of this configuration exhibits a strong dependence on the arrangement of Ls and Cs. With the tuning circuit consisting of Cs2 and Ls2 only, the start-up time is 325 ms. If instead the same component values are installed for Cs1 and Ls1, the start-up time is 550 ms.




**Schematic 7:** Low Noise Oscillator

### IX. Other Effects of Tuning Arrangement

The load capacitance presented to the resonator affects the oscillation frequency. If Cd1 and Cd2 are not considered in simulations, the arrangement of the tuning elements will not influence the frequency. In reality, the effects of the enclosure capacitances impact the frequency as well as the sensitivity of the frequency to $C_L$ changes (pullability).

If the circuit in Schematic 2 is analyzed with a 5 MHz resonator having a C1 of 1 fF, Cs = 10 pF and Cd2 = 1 pF, the frequency will show a change of 4.2 ppm when Cd2 is removed. The pullability of the circuit is also influenced by the presence of Cd2. With Cd2 at 1 pF, the frequency changes 19.4 ppm for a change of Cs from 10 pF to 40 pF. When Cd2 is removed, the pullability increases to 22.6 ppm for the same range of Cs.

The pullability of the circuit shown in Schematic 3 with Cd1 = Cd2 = 1 pF when Cs varies from 10 pF to 40 pF is 20.6 ppm. If Cd2 is removed from the circuit, the pullability remains unchanged at 20.6 ppm. When Cd2 is removed, the resulting frequency change is 0.4 ppm.

The difference in frequency of the two circuits with Cs = 10 pF and Cd1 = Cd2 = 1 pF is 1.6 ppm.

### X. Conclusion

It is demonstrated that using the conventional four element quartz resonator model may cause incorrect simulation results of start-up and open loop gain. Taking the enclosure capacitances into account is important for oscillator simulations. Therefore, the six element resonator model presented in this report will improve the accuracy of crystal oscillator simulations. This is particularly true for lower frequency Colpitts oscillator configurations.

Certain oscillator applications require large frequency deviation over the EFC voltage range. The absolute frequency as well as frequency deviation can be predicted more reliably if the enclosure capacitances are included in the analysis, regardless of the circuit topology.

The designer should pay close attention to the arrangement of the elements within the oscillator loop to effect optimization of the start-up time, start-up reliability and frequency deviation characteristics.

### Acknowledgement

The author expresses gratitude to Perkunas J. Kavolis for the enlightening discussions of crystal modeling and to Robert F. Smith for fabricating the breadboards.

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[2] Parzen, Benjamin, "Design of Crystal and Other Harmonic Oscillators", 1983, page 75

[3] Ibid., pages 69-71

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