In the previous part of this series, we had discussed some of the important specifications of a crystal such as crystal pulling range, drive level and crystal stability with respect to temperature variations and aging. In this segment, we continue our discussion on the remaining specifications such as startup time, crystal overtone and spurious modes.

**Startup Time:** Crystal Oscillator startup time is a very important parameter that a system designer must look in the datasheet before using it for their application. The oscillations don’t build immediately after powering up the device; it takes time that ranges between few milliseconds to seconds sometime. The startup time depends on various parameters such as crystal frequency, rated load capacitance, gain of inverting amplifier and negative resistance. Some of the salient reasons for long startup times are:

- The crystals, which have very high Q and/or have high rated load capacitance comparatively, start slower.
- Crystals with high ESR tend to start slower compare to a lower ESR crystal as high ESR results in low Oscillation Allowance (margin to negative resistance).
- A weak loop gain will also result in long startup time because during startup a comparatively high amplification or gain is required than that for a stable oscillation.

Sometime oscillator circuit designers provide a provision to override the load capacitance, which results in improved negative resistance at startup, once the oscillations are achieved the load capacitance is released to run the crystal at rated frequency. Note that for such arrangement the load capacitance is integrated inside the chip so that a simple switch can cut those during startup.

Figure 1 shows the behavior of crystal during startup. It can be noticed from the figure that after power up the oscillations doesn’t build up immediately. After sometime the oscillations start building with increasing swing and finally get stabilized. The total start time in this example is ~600µs. The timescale on the oscilloscope was adjusted to capture entire range on single screen that’s why the individual oscillation cycles are not visible.
Crystal Overtone and Spurious Modes: Crystals can offer many resonant modes that can be exercised by proper design of crystal oscillator. The major response and mostly desired one is the “Fundamental Mode” which has the strongest energy and contributes the most in building the oscillations as well as the lowest ESR. Apart from its fundamental mode, crystals may respond to higher resonant frequencies called “Overtone”. Overtones are always odd number i.e. next to fundamental mode; crystals may have 3rd overtone, 5th overtone, 7th overtone and so on. Overtone response should not be confused with harmonics of fundamental frequency. Harmonics is always an integer multiple of lower frequency, but overtone is not an exact multiple of fundamental frequency. However, overtone response is in close range to harmonics response of same order e.g. a 3rd overtone response of crystal typically lies in range of 2.8 to 3.2 times of fundamental response. Overtone modes are, in most applications, unwanted and may be excited to lesser or greater degrees by different circuits.

Care should be taken especially when using crystals in untuned digital circuits as unwanted modes may unexpectedly dominate due to noise, high drive level or low negative resistance. This can be achieved by either limiting the 3rd overtone mode of crystal to sufficiently outside the range of electrical 3rd harmonics of oscillator or by minimizing the amplifier gain of oscillator but still providing sufficient negative resistance to ensure startup.

An equivalent electrical model of crystal in overtone mode is shown in Figure 2. It is found that the motional capacitance $C_X$ (where $X$ implies the overtone mode) decreases with the increase in overtone mode. It follows an approximate law, where the capacitance for the $X^{th}$ overtone is the capacitance for the fundamental divided by the square of the order of the overtone (Equation 1). Also the ESR increases with higher overtones.
Figure 3 below shows the extended reactance curve of crystals showing the overtones. It can be seen from the curve that crystal behaves like a pure resistor at some frequencies and is in capacitive or inductive region at other frequencies. The major responses are when electrical properties of oscillator facilitate the conditions for crystal to operate in that mode. That again tells us that crystal operation mode are not only decided by crystal parameters alone but the electrical circuitry as well that is put in the oscillator design which allows to filter other modes of crystal operation and allowing it in one mode of operation.

\[ CX_1 = \frac{C_1}{X^2} \]

Equation 1

Figure-2: Crystal Equivalent circuit with Overtone Branches

Figure-3: Crystal Overtone and Spurious Response
Despite saying that overtone modes are undesirable in majority of applications, but they may be highly recommended in certain application e.g. a 3rd overtone mode is preferred over fundamental mode of same frequency in conditions where the crystal needs to be tolerant against strong mechanical vibrations as 3rd overtone mode has higher mechanical stability. Take an example of 3rd overtone crystal oscillator design, which can be achieved (in the easiest way though other methods are also available) by slightly extending the Pierce Parallel resonant oscillator. An additional branch of Inductor (L3) and Capacitor (C3) in series is added in parallel to CL2, as shown in figure 4. The values of L3 and C3 are so chosen that these form a parallel resonant circuit at a frequency about mid-way between fundamental and third-overtone frequency.

The fundamental mode is suppressed by filter characteristics of L3-C3 network and it makes the whole circuit to appear capacitive at 3rd overtone frequency, which is desired for 3rd overtone operation. By proper design approach other modes of operation can also be achieved.

Let’s examine the Figure 3 once again, and we can note that there are crystal resonant modes available other than Fundamental and Overtone modes. These responses are called Spurious response. These modes are low energy modes but they may cause an oscillator to be tuned at undesired frequency. Spurious response shows up in range of few kHz next to the desired resonant mode. These modes can be either temperature dependent where a spurious response may move through the main node due to different temperature coefficients, or can happen when crystal is subjected to mechanical vibrations which modulate the resonance frequency to a small degree.