Quartz Crystals in Vibratory Environments

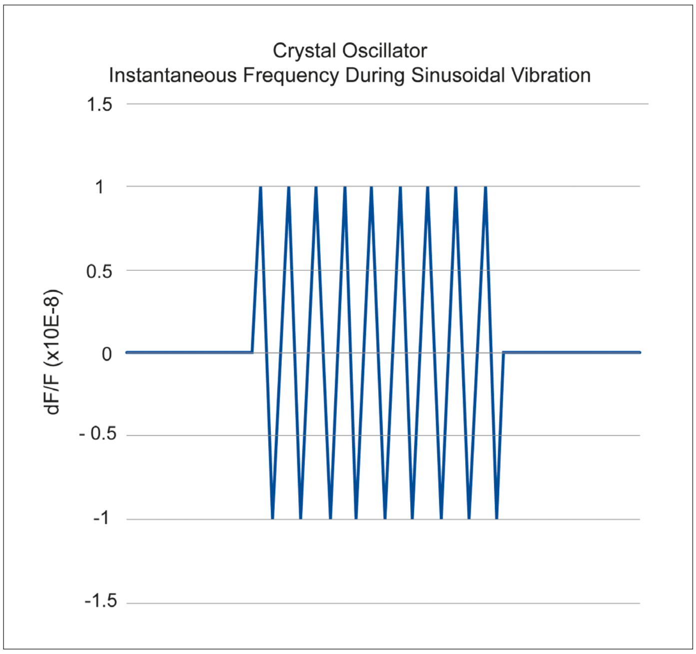

Figure 1

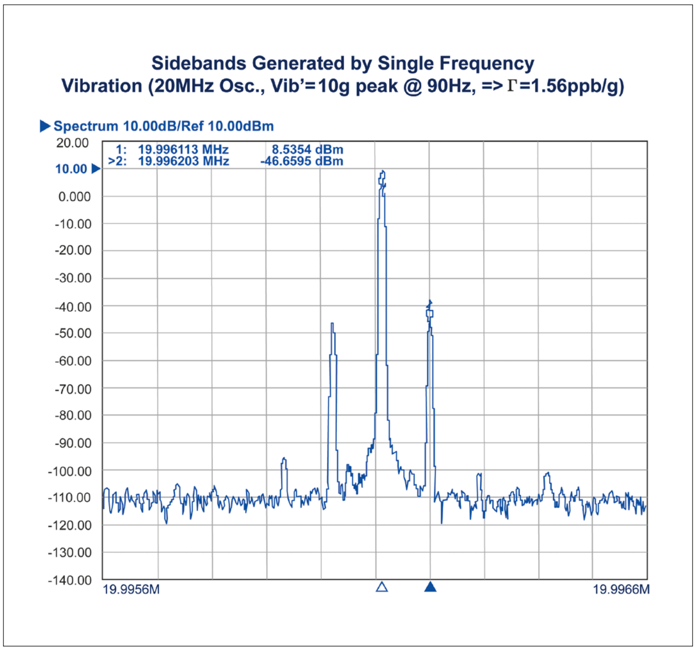

Figure 2

Quartz crystal oscillators are commonly used to provide a very stable frequency source or reference in many electronic systems. Crystal oscillators will provide a very clean and relatively noise-free signal when they are in a benign environment and are not experiencing any movement or acceleration forces. But any change in position or periodic movement such as vibration will cause a change in the operating frequency of the oscillator. In many applications, these frequency changes are extremely small and go unnoticed, having no noticeable effect on the device performance. But for systems that experience high levels of vibration, the output signal will be significantly degraded and may disrupt system operation.

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The acceleration sensitivity of a crystal is also commonly referred to as "g-sensitivity". This is usually denoted by the Greek letter Gamma.

Acceleration forces cause a change in the resonant frequency of all Quartz Crystals to some degree. This is primarily due to stress applied to the active area of crystal through the mounting structure. This change is relatively very small. A typical quartz crystal will measure $<2 \times 10^{-9}$ per g (0.002 ppm/g or 2 ppb/g). This effect goes unnoticed in many applications but can become very significant in the presence of vibration. The acceleration sensitivity is linearly proportional to applied force up to >50g's (depending on the crystal mounting structure). One other aspect to be considered is that g-sensivity is a vector quantity and therefore the frequency shift is highly dependent on the direction of the applied force.

Sinusoidal Vibration

Crystals in many applications experience some level of periodic vibration. The instantaneous frequency of the crystal will shift according to the direction and magnitude of the applied force. During a periodic vibration, the direction of the force is continuously reversing so that the frequency shift goes from positive to negative. This essentially applies FM modulation to the RF signal. The magnitude of this frequency shift may therefore be determined by measuring the relative level of the vibration induced sidebands and using FM modulation theory. The acceleration or "g" sensitivity of the oscillator is then found by using the known peak value of the vibration and normalizing the peak frequency shift to 1 g (**Figure 1**).

Figure 2 shows the spectrum of a 20 MHz crystal oscillator while being vibrated at 90 Hz with a 10 g peak magnitude. The formulas show the conversion from the sideband level to the acceleration sensitivity which is normally denoted as gamma.

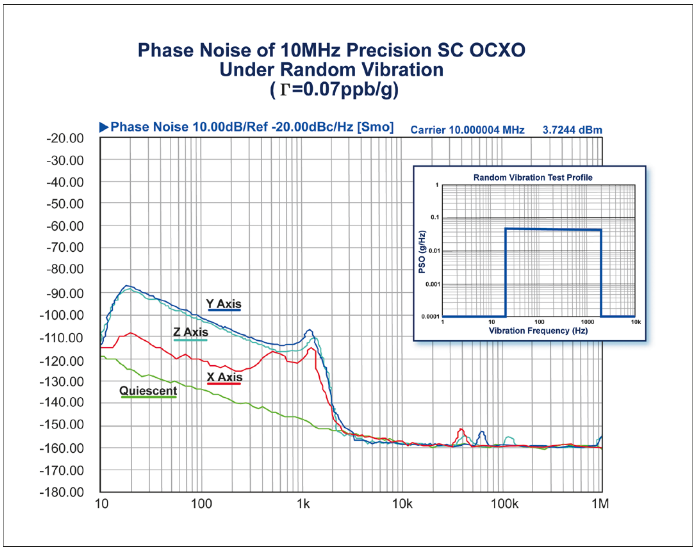

Figure 3

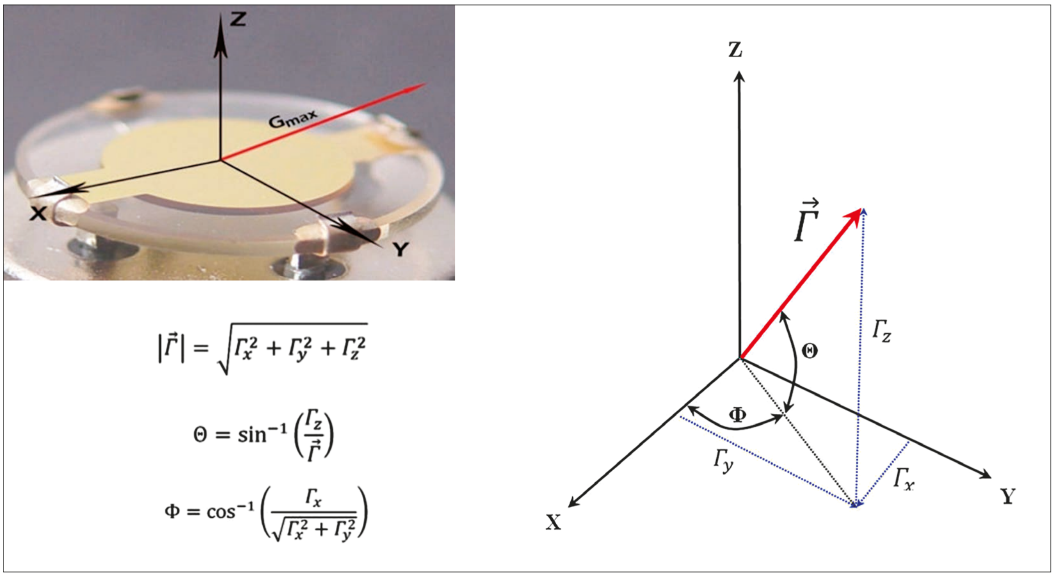

Figure 4

Random Vibration

In most real-world applications, however, the vibration experienced is not a simple periodic force. Systems that operate on mobile platforms will experience random vibrational energy which is spread across the spectrum from less than 10 Hz to10 kHz or higher. Instead of being defined by a discrete peak vibration level, the random vibration energy is spread over a certain bandwidth and is described by its power spectral density in g^2/Hz, similar to a noise profile.

Each platform or vehicle will have its own unique random vibration signature which will be used when doing validation and qualification testing. But it is useful to characterize oscillators by using a flat random profile over a certain bandwidth and observing the oscillator phase noise response. It is possible to calculate the g-sensitivity from a random profile as well. But instead of using the peak value of vibration, the power spectral density is used. The formula in **Figure 3** shows the calculation for g-sensitivity given the PSD level at a specific offset or vibration frequency.

Figure 3 shows the phase noise of a very stable 10 MHz ovenized oscillator with an SC cut crystal during random vibration. This illustrates that even though an oscillator may have a quiet noise profile when at rest, the phase noise is significantly degraded by more than 30 dB a vibration level of only $0.05g^2$/Hz. This also points out the vector nature of the quartz showing different results depending on the direction of the applied force.

Vector Properties

In order to get a picture of the full 3-dimensional characteristics of the crystal, it is necessary to measure the acceleration sensitivity in three orthogonal axes. **Figure 4** depicts a coordinate system for defining the magnitude and direction of the

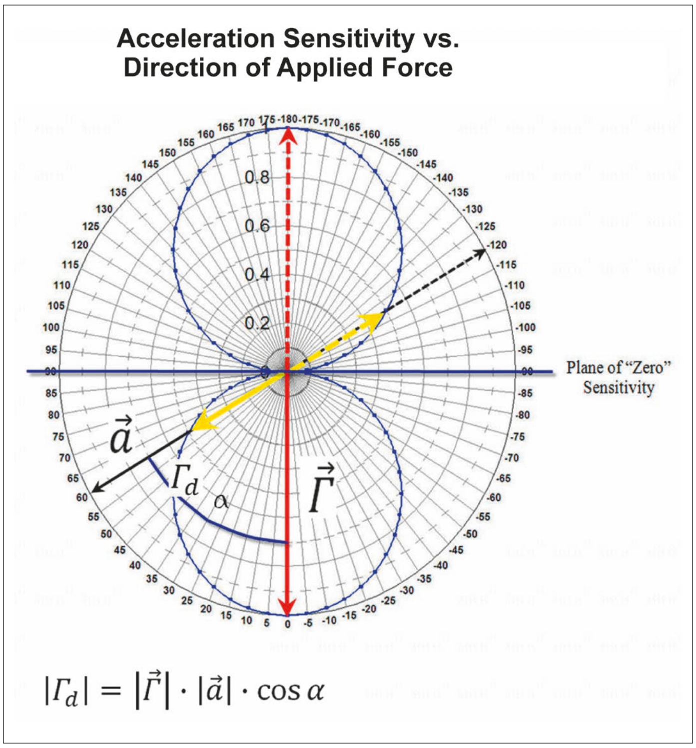

Figure 5

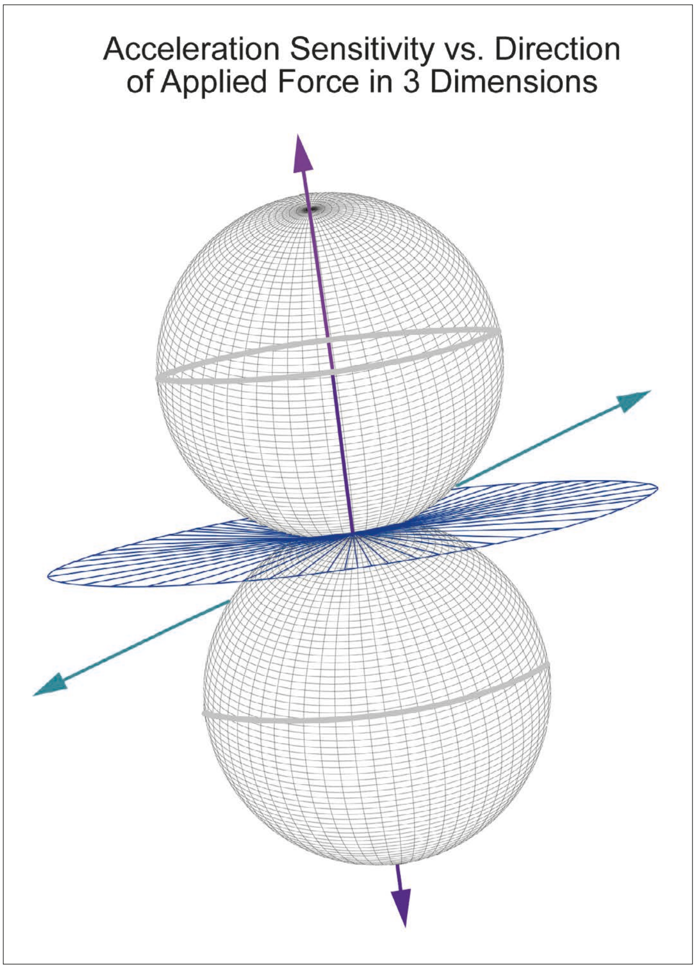

Figure 6

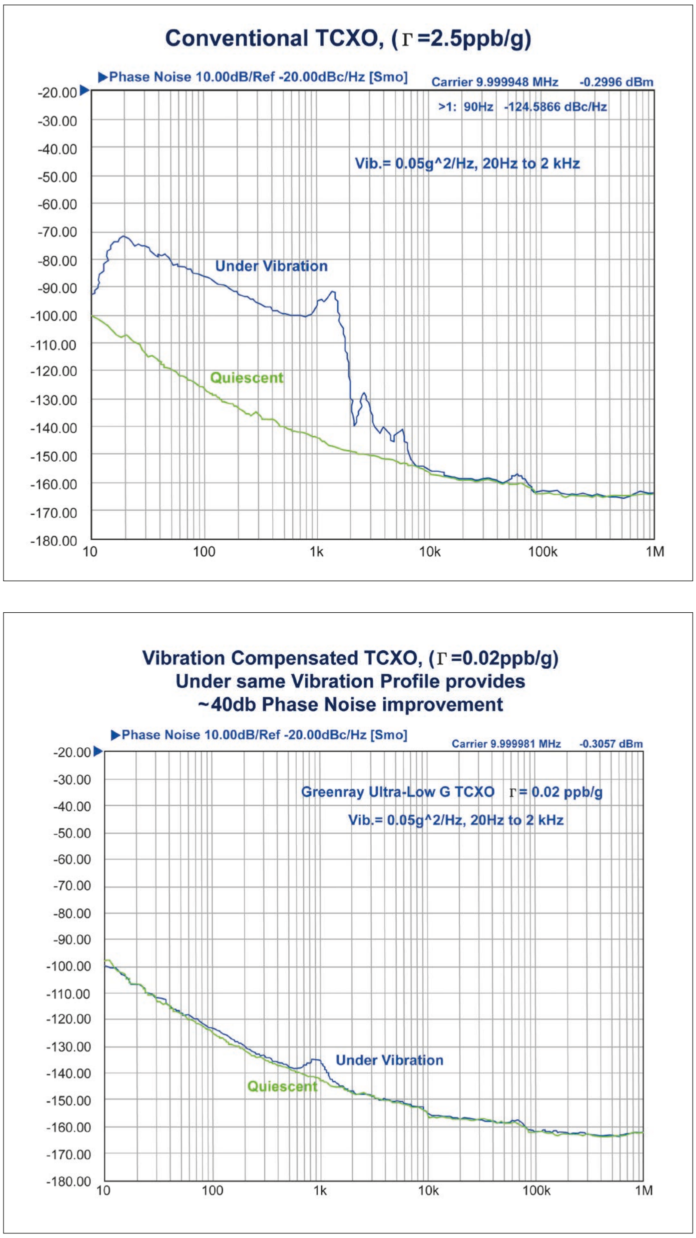

Figure 7

G vector. The maximum g-sensitivity vector, G_{max}, usually does not align exactly with one of the measured axes relative to the crystal package. But by using trigonometric identities the magnitude and direction of the G_{max} vector can be determined.

The effect of changing the direction of the acceleration force is shown in **Figure 5**. The maximum frequency shift occurs when the force is in the same direction as the G_{max} vector and decreases as the cosine of alpha as the direction changes. Figure 5 illustrates the effect in two dimensions while **Figure 6** shows how this also applies in three dimensions. Another potentially useful aspect that can be seen here is the plane of "Zero Sensitivity" that exists when the acceleration forces are applied in the plane that is perpendicular to the G_{max} vector. If a crystal-based device in a particular system experiences vibration forces that are primarily from one direction, orienting the oscillator so that the sensitive axis is perpendicular to the force can result in a substantial reduction of the vibration induced effects, see **Figure 7**.

Mitigation Methods

There are also methods of compensating for the effects of vibration on a crystal oscillator. Active cancellation methods can be used. These methods employ an accelerometer to sense the level of vibration being experienced by the crystal. This signal is then fed back to the oscillator circuit after being scaled and phase shifted properly to cancel out the instantaneous frequency shift caused by the vibration. If the magnitude and direction of the G vector are known, it is possible to substantially reduce the effect by using two crystals which are positioned so that the vectors are anti-parallel, pointing in opposite directions. The two crystals are then connected electrically in either a parallel or series configuration and connected to an oscillator circuit. This type of passive compensation can reduce the effects of vibration on an oscillator substantially. The graphs below show the improvement in the phase noise under random vibration that can be achieved with this technique. This passive compensation method is being employed in miniature TCXOs to reduce the effective g-sensitivity to less than $8x10^{-11}$ per g.

Another method for reducing the effects of vibration on a system is to use imechanical vibration isolation. This can be very effective at reducing high frequency energy; however, isolation is only achieved above the natural frequency of the isolator. This places constraints on the size and weight of the components if isolation at low frequencies is needed. So, it is often not practical to use mechanical isolators for components in small assemblies, see **Figure 8**.

So, as it has been pointed out here, if one understands the nature and magnitude of the vibration that will be experienced by a system, the effects that this vibration will have on the oscillator signal can be predicted and possibly mitigated to some extent. ◄

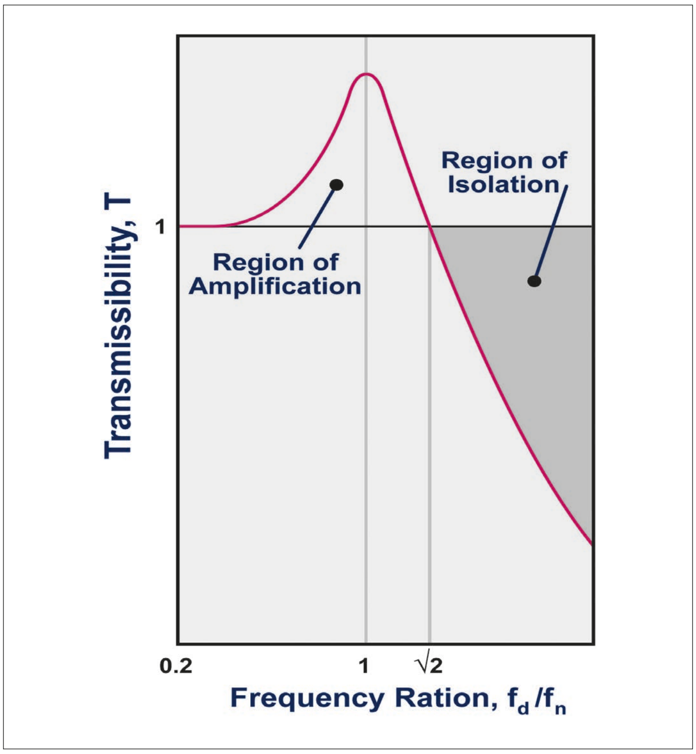

Figure 8