Crystal Oscillators – Low Phase Noise under Vibration

by Liz Ronchetti, Wenzel Associates

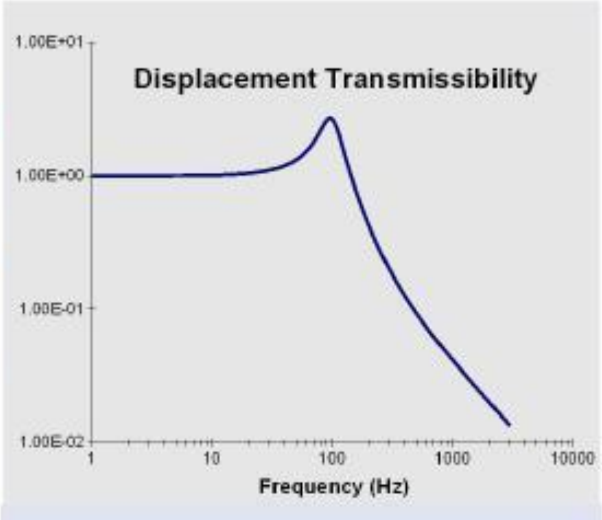

Figure 1: Calculated isolation Response with 100 Hz Resonance

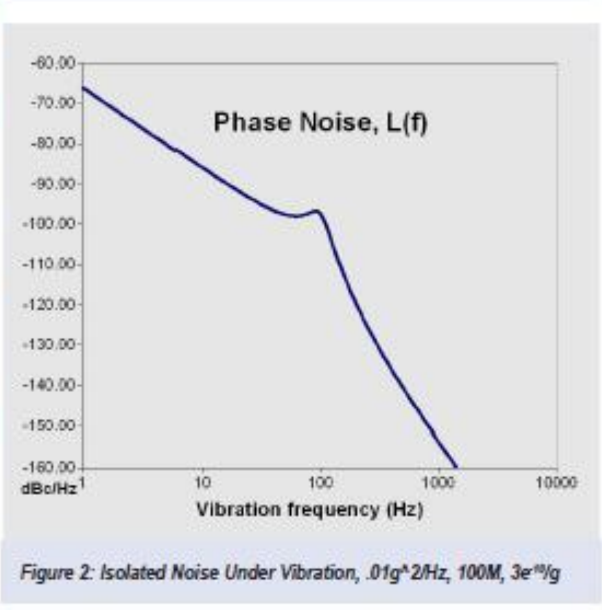

Figure 2: Isolated Noise Under Vibration, .01g^2/Hz, 100M, 3e^{-10}/g

Precise Frequency under Vibration

We hear news of drone attacks that are swift, precise, and dramatic. But the designers of the electronics in commercial and military hardware see these realities as paragraphs in specification sheets, in test procedures and mechanical CAD drawings. Designers in the frequency control arena must ensure that their equipment performs well over a combination of environments.

Precise frequency is important in radar systems for targeting, fire control and threat detection. Critical communication systems that use agile frequency hopping must stay connected in increasingly busy and hostile electronic airspace. GPS receivers provide precise locations, but limited or absent GPS signals can require navigation equipment to free-run for seconds or even minutes. Satellite communications systems demand very precise frequency, and in Radio Astronomy the quality of the high resolution images can be tied to the quality of the frequency sources. The most critical specifications in precise frequency generation are phase noise, spectral purity, and frequency stability and all must be met over temperature and under vibration.

Wenzel Associates designs and manufactures crystal oscillators, fixed frequency systems, integrated microwave assemblies, and synthesizers to X-band. Many are custom designs for environments which require very low noise performance under vibration. Several techniques are used and include very low-g sensitivity crystals from our Croven Crystals division in Canada, vibration isolation systems and special compensation techniques.

Crystal Sensitivity

Quartz crystal oscillators are the basic building blocks in most low noise frequency generation systems and their crystals change frequency slightly when accelerated. Because frequency is one of the few parameters in which parts per billion can be significant, even low vibration levels can hurt performance.

The sensitivity to acceleration means that the random and periodic mechanical vibrations found in many equipment bays and instruments can induce significant phase noise in high-performance crystal oscillators. Portable instruments are exposed to significant vibration in trucks, tanks, ships, drones, jets, helicopters and man-packs. Stationary instruments may be close to vibrating machinery, shaken by nearby cooling fans, or affected by a ship's yaw, pitch and roll. Crystal holders, circuit boards and cases can exhibit mechanical resonances, giving the oscillator substantially increased noise degradation at particular frequencies of vibration. Careful design and crystal mount selection can move these resonances to high frequencies where mechanical damping is more effective and can be included in the design.

This acceleration sensitivity, or g-sensitivity, may be observed in stable oven oscillators by employing a two-g tip-over test. When an oscillator is turned upside down, the force on the crystal changes by two g, or plus one g to minus one g. A typical SC-cut 10 MHz crystal will change about 0.01 Hz, which gives a sensitivity of about 0.005 Hz per g. It is common to specify a crystal or an oscillator as having a sensitivity of <5e-10 per g per axis, which represents the one-g sensitivity in a given axis. Average VHF crystals, especially those above 70 MHz, will often have less g-sensitivity than lower frequency crystals, but the sensitivity can vary significantly from one crystal to the next and from one crystal holder type to the next. Changing stress on other components or even slight chassis movement can also shift the frequency, adding to the oscillator's overall sensitivity.

Acceleration sensitivity is a vector quantity which may be expressed by a magnitude and direction or as the summation of three orthogonal vectors usually aligned with the sides of the oscillator's case. The induced phase noise may be calculated from the following equation, where the acceleration is the g- level for sine wave vibrations or the square root of twice the power spectral density in a one hertz bandwidth for random vibration:

L(f) = 20 log ((acceleration sensitivity x acceleration x oscillator frequency) / (2 x vibration frequency))

A spreadsheet is available on Wenzel's website http://www.wenzel.com/documents/spread1.htm that provides information on damping and the effects of vibration on phase noise. The first portion

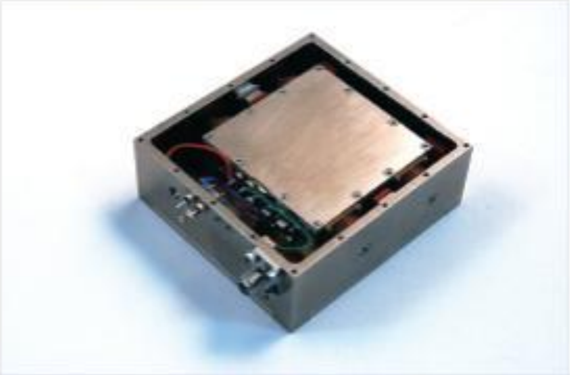

Figure 3: Wenzel VHF Citrine Oscillator, Vibration Isolated

Figure 4: Citrine Oscillator/Amplifier in System

of the spreadsheet calculates the effect of a single degree-of-freedom vibration isolation system given the natural frequency and the damping factor entered. See **Figure 1**, which shows the isolation response.

Vibration Isolation

The most common approach to reducing vibration-induced phase noise is to select low sensitivity crystals and isolate the crystal oscillators with isolators with a low natural frequency. Small, omni-directional elastomer or stainless steel shock mounts may be contained within the oscillator package when size is critical. When space permits, an external vibration mount can provide a lower natural frequency, taking advantage of the entire oscillator's weight along with the weight of the mounting plate and additional ballast if necessary. Vibration mounts must be chosen carefully since many materials exhibit substantial stiffness changes over temperature and most mounts exhibit direction dependent isolation. The designer must allow sufficient room around the isolated assembly to prevent impact with other objects with normal vibration levels. Many shock mounts are non-linear, becoming significantly stiffer at the deflection extremes, but to take full advantage of this non-linearity, the designer must allow the mount sufficient room to stretch. Attaining a low resonant frequency below about 100 Hz can prove difficult when mounting small components like crystal oscillators. Interconnecting cables should be flexible and secured so that flexure occurs along the length of the cable and not at the ends. A short, stiff cable can devastate the isolation characteristics of good mounts.

The second section of the Wenzel spreadsheet shows the phase noise of an oscillator with a specified acceleration sensitivity mounted on the vibration damping system. The vibration isolation system may be removed from the calculation by entering a very high natural resonance frequency (1e6) so that no vibration damping occurs over the frequency span shown. Vibration profiles may be entered by changing a scaling factor, either increasing or decreasing the level from some nominal point. The frequency points may be changed or additional columns may be added or removed.

This spreadsheet displays the effects of vibration on the phase noise of an oscillator given a single value for the acceleration sensitivity. **Figure 2** assumes that the crystal and other mechanical components have no significant resonance and the acceleration sensitivity in the axis of the vibration is accurately described by a single value over the frequency range of interest. A real-world oscillator will exhibit some resonance and the acceleration sensitivity will be direction dependent. The real-world oscillator may also have static phase noise which may be greater than the vibration induced noise. Note that improving the static phase noise of an oscillator may not improve the performance of the oscillator under vibration if the vibration induced noise is significantly greater than the static noise.

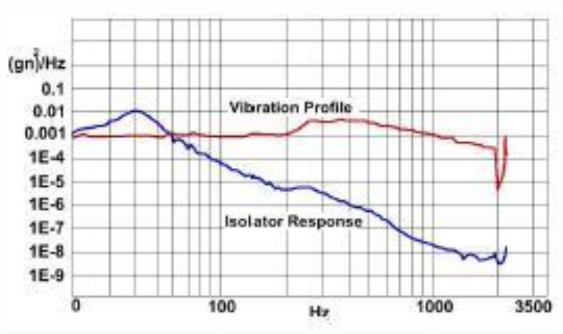

Figure 5: Vibration Profile and Isolator Response with a 40 Hz Resonance

Wenzel has many vibration isolated oscillator designs, and vibration isolation is standard in Wenzel's Citrine VHF Low Noise and Ultra-Low Noise series oscillators. The Citrine can be provided with mounting holes for isolators or the oscillator on shock isolators can be mounted into a standard external Citrine housing. When isolated in the housing, vibration testing is provided at Wenzel for the system as a whole. In most cases, the Citrine's internal housing has two cavities, one for a very low noise crystal oscillator and a second cavity that houses a PLL or a x2 stage; an odd order multiplier x3, x5 or x7 stage; or high output amplifiers or dividers. The additional cavity adds mass, which can drive the resonant frequency of the isolators below 70 Hz. The mounts in the system in **Figure 3** are rated for full MIL temperature range of -54 to +125C.

Actual test data is provided below for the vibration response of a miniature low noise oscillator in a 40 Hz resonant damping system. The vibration profile, 0.001 g^2/Hz 10-200 Hz, 0.004 g^2/Hz 200-500 Hz, 0.00025 .001 g^2/Hz 2000 Hz is displayed above with the resultant damping profile. The attenuation is significant and at 300 Hz from the carrier, the vibration level drops from 0.004 g^2 per Hz (4e-3) to about 4e-6 per Hz. See **Figure 5**.

The actual phase noise performance in **Figure 6** smoothly follows the damping system's performance and provides excellent phase noise of -114 dBc/Hz at 100 Hz and -156

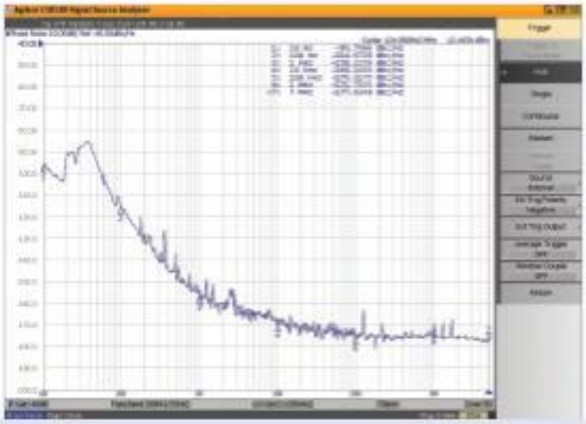

Figure 6: Phase Noise Performance under Vibration, 125 MHz Isolated System

Figure 7:ONYX IV 1" Square Rugged Oscillator

dBc/Hz at 1 KHz. The sensitivity of these oscillators is typically 2 to 3e-10/g per axis. This oscillator is a custom designed very low noise 125 MHz oscillator with noise floors at -176 dB/Hz.

It is worth noting that the vector nature of the acceleration sensitivity means that the oscillator will be most sensitive to vibration in one particular direction and that there is a plane where the sensitivity approaches zero (any direction orthogonal to the sensitivity vector). In critical systems, the oscillator may be positioned so that the sensitivity vector points in the direction of least vibration or in the direction of best isolation when a vibration isolator is used.

Vibration Compensation

There have been efforts to compensate crystal oscillators by pointing an accelerometer in the direction of the sensitivity vector to develop a correction voltage to apply to the oscillator's electrical tuning. An enhanced version of this approach could use a digital signal processor (DSP) to convert the rather linear accelerometer output into the rather non-linear profile needed to correct the phase of the oscillator, possibly even compensating for mechanical resonance. Modeling the non-linear behavior of vibration systems has met with some success at reducing noise levels.

A special Bootstrapping compensation scheme developed at Wenzel Associates makes use of a PLL technique which uses two crystal oscillators phase locked together where the correction voltage is proportional to the frequency difference that would be presented if the oscillators were unlocked. When the frequency difference is a linear and repeatable externally induced effect or a linear time related effect, then this correction voltage may be used to generate a compensating signal. The properly scaled compensation is applied with the same polarity to the electrical tuning of both oscillators, boostrapping their frequencies by the same amount. By bootstrapping both oscillators, the phase locked loop remains unaffected and the linear perturbance is removed. Non-linear frequency perturbations may also be compensated, but the compensating signal will require non-linear processing instead of simple scaling. The technique requires that the two oscillators have significantly different sensitivites to the external influence; vibration in this case.

Wenzel builds both VHF and UHF Bootstrap oscillators in a 5 x 6 x 2.2" assembly. Two crystal oscillators are phase locked and since the sensitivies are different, a fast PLL's tuning voltage varies in proportion to this difference and the vibration level. By scaling this voltage and applying it to both oscillators the vibration sensitivity is reduced. This is the only technique that we are aware of that provides relatively consistent vibration compensation over vibration profiles from 5 Hz to 2kHz.

Low Vibration Sensitivity in a Small Package

When space is at a premium and low noise and low-g sensitivity are critical, the best way to minimize phase noise performance may be to specify and grade very low g-sensitivity crystals. Wenzel's Croven Crystals division in Ontario is regularly producing crystals with sensitivities down to 2e-10/g per axis. Wenzel Associates has incorporated these crystals into two rugged miniature 1 x 1 x 0.5" oscillators that are available with graded low-g performance per axis. The Wenzel low phase noise Onyx IV Oven Controlled Oscillators are readily available at 10 MHz and 100 MHz, and can be guaranteed to <3e-10/g and <2e-10/g per axis. The 10 MHz oscillators come with Sine, TTL or DUAL outputs and noise floors of -165 dBc/Hz. The 100 MHz oscillators provide sine outputs and may be specified with -175 noise floors.

There are many applications where frequency and phase noise stability are critical, especially in military and airborne equipment. Careful design, testing to MIL-standards and special attention to environmental requirements overall ensure that the equipment is fit for use and will maintain its long-term accuracy in the field.

Citation: Many of these details are available on Wenzel's website in the Library under Shock and Vibration. Thanks to Charles Wenzel, who provided major input to this article.