Vibration isolation of crystal oscillators

Introduction

Crystal oscillators can generate stable signals with very low phase noise, which may be used directly or as references for frequency synthesisers. The Pascall OCXO is designed to offer the lowest possible phase noise, both broadband and close to carrier, at frequencies typically in the range 50-130MHz.

High-vibration environments can prevent the inherently low phase noise of a crystal oscillator from being realised. The mechanism is usually dominated by the vibration sensitivity of the crystal, which converts constant acceleration into a shift in its resonant frequency. The result can be discrete FM sidebands and / or increased phase noise, depending on the nature of the vibration.

Anti-vibration mounting acts as a mechanical low-pass filter, which attenuates the vibration experienced by the oscillator at frequencies above the mechanical resonance. Practical implementations are rarely ideal, but involve compromises imposed by critical specification parameters, size / mass limits and the vibration profile the assembly must survive.

Calculating added phase modulation

Crystal vibration sensitivity is generally expressed as a normalised parameter defining the proportional change in frequency for a given acceleration, e.g. $1\text{x}10^{-9}$/g.

If an 80MHz crystal with this sensitivity were subjected to a constant acceleration of 5g say, the change in its resonant frequency would be $80\text{x}10^{6} \text{ x } 1\text{x}10^{-9} \text{ x } 5 = 0.4$Hz.

Sinusoidal vibration example:

Consider a 100MHz crystal oscillator with a vibration sensitivity of $2\text{x}10^{-9}$/g, subjected to 4g peak sinusoidal vibration at 50Hz.

Frequency deviation = $100\text{x}10^{6} \text{ x } 2\text{x}10^{-9} \text{ x } 4 = 0.8$Hz peak.

Phase deviation = $0.8 \div 50 = 0.016$ radian peak.

Sideband level = $20\log(0.016\div2) = -41.9$dBc.

Random vibration example:

Consider the same oscillator, subjected to random vibration of $0.01\text{g}^2/\text{Hz}$ ($\equiv 0.1\text{g}/\sqrt{\text{Hz}}$) from 10-1000Hz.

FM noise density = $100\text{x}10^{6} \text{ x } 2\text{x}10^{-9} \text{ x } 0.1 = 0.02\text{Hz}/\sqrt{\text{Hz}}$.

SSB phase noise at 10Hz offset = 20log(0.02 ÷ (10 x √2)) = -57dBc/Hz.

SSB phase noise at 1kHz offset = 20log(0.02 ÷ (1000 x √2)) = -97dBc/Hz.

The -20dB / decade phase noise slope is equivalent to flat FM noise, which results from a flat acceleration profile.

Real-life results

The calculations above give a good general indication of what to expect, but the actual situation tends to be more complicated. Figure 1 shows the phase noise of a 100MHz OCXO, measured both with no vibration applied, and with a random profile of $0.04g^2$/Hz from 15-1000Hz, falling to $0.01g^2$/Hz at 2kHz.

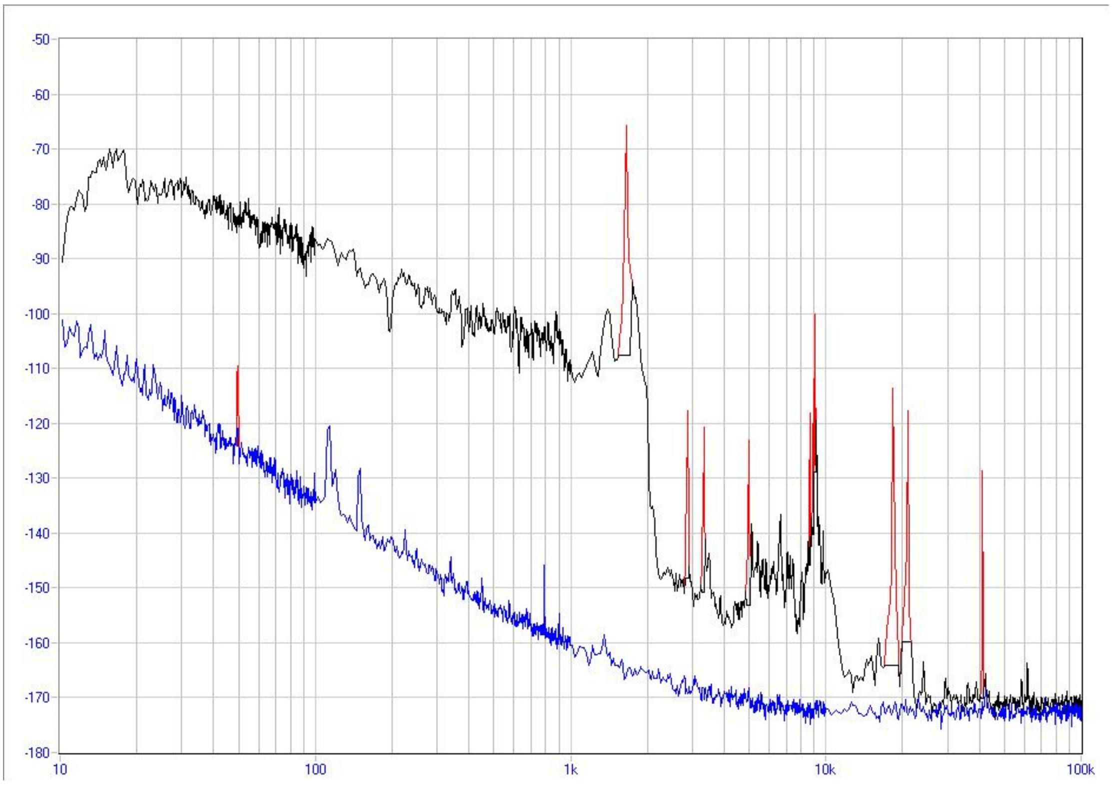

Figure 1: 100MHz OCXO phase noise

Below 1kHz offset, the phase noise with vibration shows the expected -20dB / decade slope. If we take the phase noise at 100Hz offset to be ~-87dBc/Hz, this gives a vibration sensitivity (in this axis) of ~$3x10^{-10}$/g.

The plot also shows how easy it is to get misleading results. Vibration measurements necessarily involve large masses of metal (in the shaker and test fixture) with high-Q resonances, which require careful positioning of accelerometers to minimise their effect. In this case a fixture resonance at ~1.7kHz was not sufficiently controlled, resulting in a large spurious peak in the phase noise plot.

The phase noise drops sharply above 2kHz offset as expected, but there is still some added noise, which may be due to non-linearity in either the shaker or the crystal's vibration response. The peak at 9kHz and its 2nd harmonic are believed to be associated with a resonance of the crystal.

Vibration sensitivity of crystal resonators

Choice of resonator is important. SC-cut crystals typically have lower sensitivity than AT-cut. (They need oven control if good temperature stability is needed, owing to their high turnover point of ~80-90°C.)

4-point mounting reduces vibration sensitivity, particularly in the axis perpendicular to the plane of the crystal. (In 3-point mount crystals this tends to be considerably worse than the other 2 axes.)

4-point mount TO5 100MHz SC-cut crystals are available with guaranteed sensitivity of $\leq\sim 5 \times 10^{-10}$/g. This is normally measured in one axis only, generally perpendicular to the plane of the crystal.

Vibration isolation

Further improvement in oscillators' performance under vibration can be achieved by the careful use of anti-vibration mounting. For small, low-mass modules such as OCXOs, elastomer mounts are the most practical, with silicone rubber generally favoured when consistent performance over a wide temperature range is required.

Figure 2 shows the transmissibility of a typical AV mounting with a natural frequency of 100Hz and damping factors of 0.1, 0.14 and 0.2.

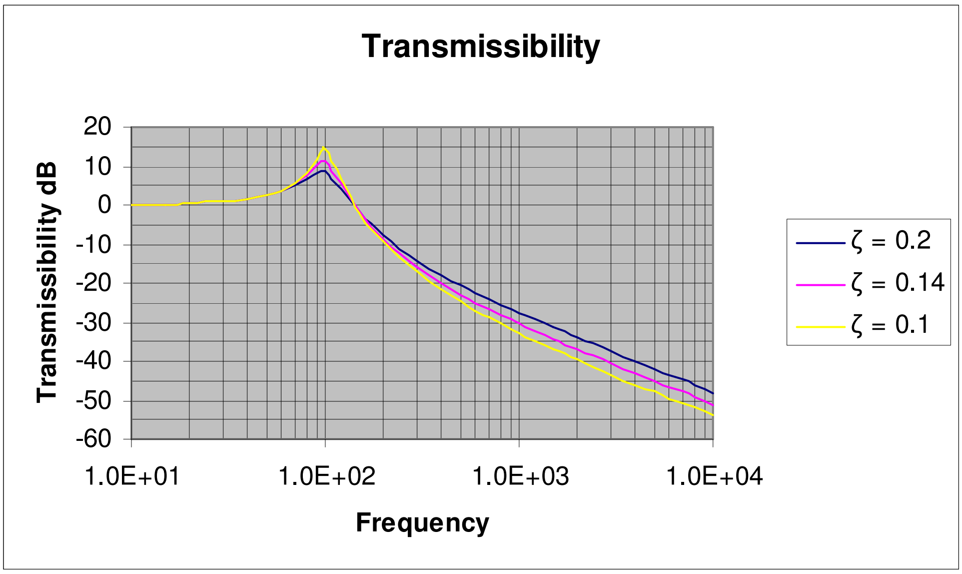

Figure 2: Transmissibility of anti-vibration mounting

This illustrates the isolation achieved at higher frequencies, but also the increase in vibration at the resonant peak. Unfortunately, greater stopband attenuation comes at the expense of increased amplification at resonance, and reducing the peaking also reduces the isolation!

To increase the stopband attenuation the resonant frequency must be reduced, by increasing the suspended mass and / or reducing the stiffness of the mounts. Ultimately this is limited by the displacement due to gravity, and hence the strain on the mounts. However in moderate to high vibration environments, the practical limit is usually determined either by peaks in the vibration profile or by the peak displacement at resonance.

At a given acceleration level, the displacement is inversely proportional to the square of the vibration frequency. This explains why it is generally impractical to achieve low resonant frequencies with small, low-mass assemblies. For any given vibration profile and isolation characteristic, the movement between the isolated module and the mounting base is the same, irrespective of the size or mass of the unit. The strain on the AV mounts is therefore inversely proportional to their linear dimensions.

Electrical connection to the suspended module is not a trivial problem. The cables and terminations must be able to accommodate the movement between fixed and isolated modules without damage, and must be of low enough mass to have only minimal effect on the system dynamics. In addition, cables carrying RF signals should not themselves add significant phase noise. As the phase shift through a cable is affected by flexing, this requirement is more difficult on small assemblies where the cable deformation is proportionally greater.

The arguments above demonstrate that it is more effective to apply vibration isolation to larger units if possible. This will enable lower resonant frequencies to be achieved, giving more stopband isolation. Longer cables will experience less deformation. Another consideration is that OCXOs are generally used to drive multipliers or synthesisers. The multiplier / synthesiser outputs, being at higher frequencies, will have higher phase noise than the OCXO, so any phase noise added by cables will have less impact.

Pascall can supply anti-vibration mounted OCXOs or larger modules. Designs tend to be specific to customers' requirements, owing to the wide variation in vibration profiles and phase noise specifications.

Figures 3, 4 and 5 show the phase noise of a Pascall AV-mounted 100MHz OCXO with random vibration applied in 3 separate axes: $0.04g^2$/Hz from 10-1000Hz, falling to $0.01g^2$/Hz at 2kHz. Each plot shows the performance with and without vibration applied.

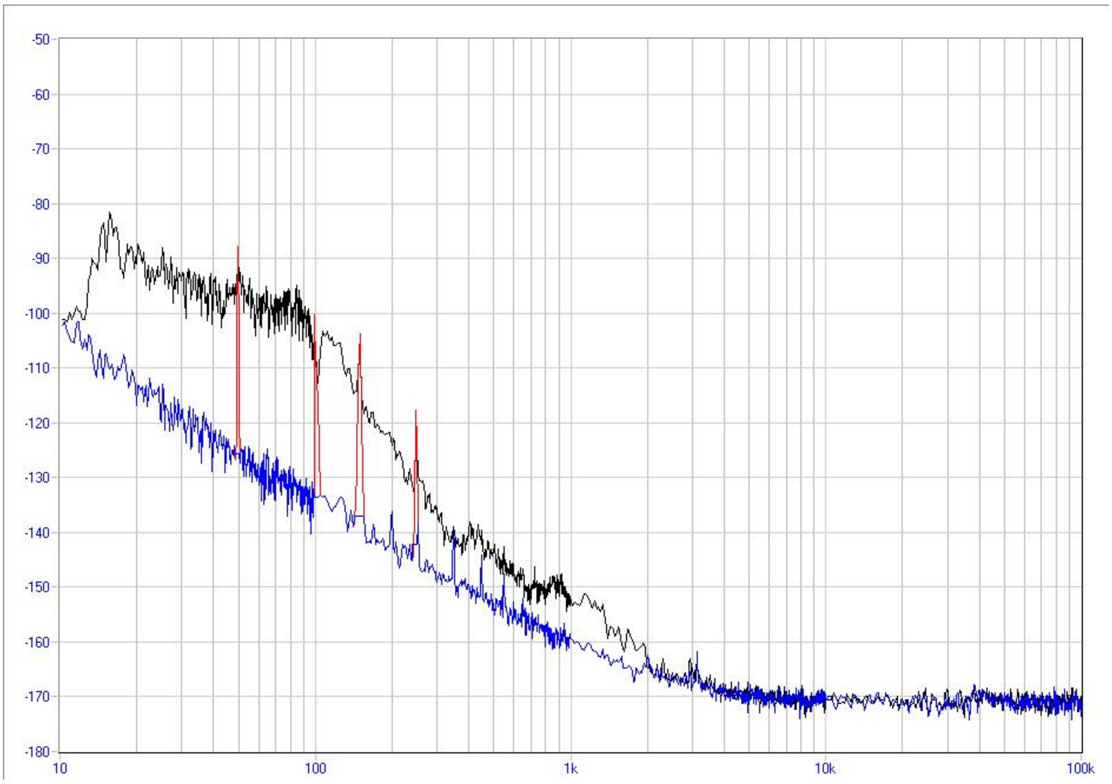

Figure 3: Lateral vibration

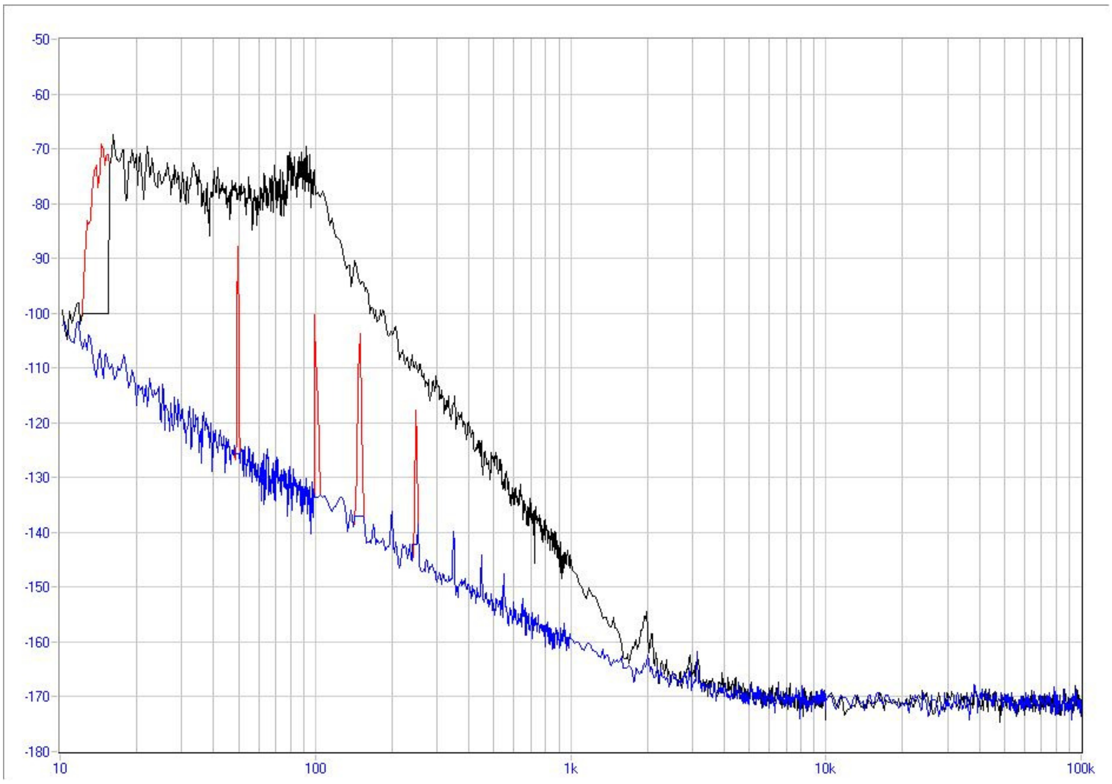

Figure 4: Longitudinal vibration

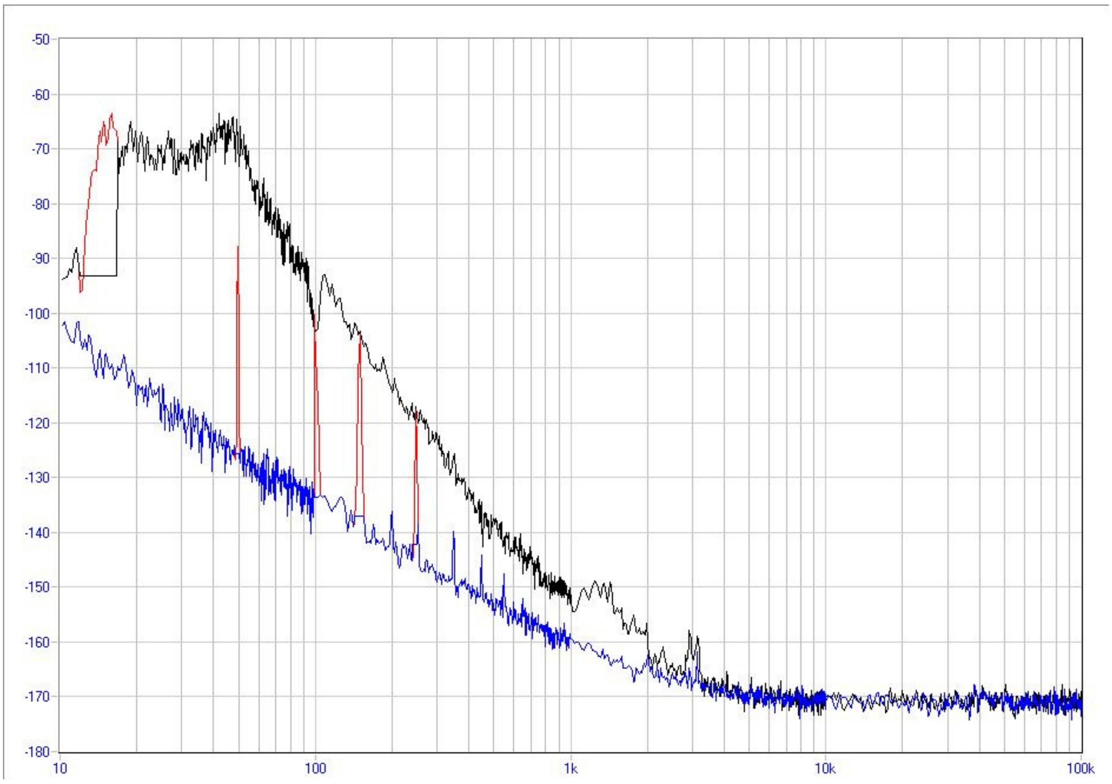

Figure 5: Vertical vibration

Compared with Figure 1, these plots show both the peaking at the mechanical resonant frequency and the improvement at higher offsets. (The mains-related products are due to earth loops in the test set-up.)

The small size and low mass dictated the use of miniature 'bobbin' style mounts, fitted in the same plane as the oscillator. This type of mount has very different stiffness in shear and compression modes, hence the different resonant frequencies in horizontal and vertical directions. The lowest practical resonant frequency was determined by the vibration profile in conjunction with the mount's rated displacement.