Vibration-Induced Phase Noise: It Isn't Just About the Oscillator

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Abstract - **Very often, actual, measured levels of vibration-induced phase noise in signal generation equipment are significantly higher than predicted. In many cases, this is because the frequency sensitivity of the oscillator or oscillator resonator to vibration was assumed to be the sole source of the degradation. As improvements in oscillator output signal static phase noise and vibration sensitivity have been realized, the effects of vibration in non-oscillator components and assemblies have become more dominant and cannot be ignored. Primary contributors to vibration-induced signal phase modulation include coaxial cables and cable connectors, narrowband filters, and enclosure mechanical resonances and non-linearities. Accurate measurement of vibration-induced, signal spectral degradation is often difficult due to the influence of both the measurement environment and test apparatus. In addition, isolating and eliminating the cause of out-of-spec hardware performance is time consuming and expensive. This paper will describe potential sources of vibration-induced signal spectral degradation and methods for obtaining and verifying adequately low vibration sensitivity in non-oscillator hardware.**

I. INTRODUCTION

Historically, many designers of signal generation hardware calculated predicted system performance by attributing all of the vibration-induced phase noise degradation to the (fractional frequency) vibration sensitivity of the oscillator resonator. A justification for doing this was that vibration induced frequency modulation (FM) in the oscillator signal, and the FM sideband level (for a given vibration level) increases as the inverse of the vibration frequency and is normally dominant source of near-carrier spectral degradation. For low noise quartz crystal oscillators, it was not unusual to apply a measured or estimated value of 0.5 to 2 parts in 10^9 per g for the crystal resonator sensitivity. Figure 1 shows the effect of typical jet aircraft vibration on phase noise for a VHF crystal oscillator when the crystal is assumed to be the sole source of oscillator vibration sensitivity. Note that the degradation is over 40dB from 10 to 2000Hz for the hard-mounted oscillator, and remains significant at low carrier offset frequencies for the same oscillator mounted on two stages of vibration isolation.

Recent advances have been made with regard to HF crystal oscillator vibration sensitivity reduction. Several oscillator vendors are now marketing 10MHz crystal oscillators with vibration sensitivities on the order of low parts in 10^{11} per g [1,2,3]. These oscillators make use of techniques similar to those first proposed by Filler and Rosati in 1981 in which accelerometers were used to generate a vibration-induced voltage directly across the electrodes of a SC-cut crystal to substantially cancel the vibration-induced frequency changes in the crystal [4]. Figure 2 shows a comparison of typical vs. required crystal vibration sensitivity for the vibration-isolated VHF oscillator of Figure 1. Also shown in the figure is an estimate of the vibration sensitivity attainable in an accelerometer-compensated, HF crystal oscillator.

In order to obtain both low (static) phase noise and low vibration sensitivity at higher frequencies, one might consider phase-locking a VHF (i.e., 100MHz) crystal oscillator to the accelerometer-compensated HF oscillator whose performance is depicted in Figure 2. Figure 3 shows the net vibration sensitivity of such a combination, using a phase-lock loop (PLL) bandwidth on the order of several hundred Hz. Improvements in crystal oscillator vibration immunity make it imperative that hardware designers additionally recognize the sources of significant signal spectral degradation that can result from vibration in the non-oscillator portions of signal generation hardware.

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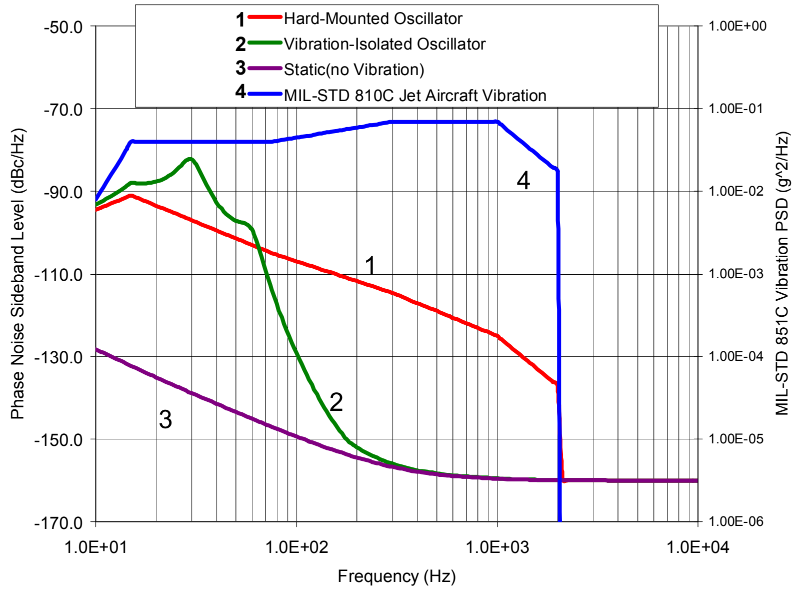

Figure 1. Vibration-Induced Phase Noise in a 10MHz Oscillator: Crystal Resonator Vibration Sensitivity = 3E-10 per g.

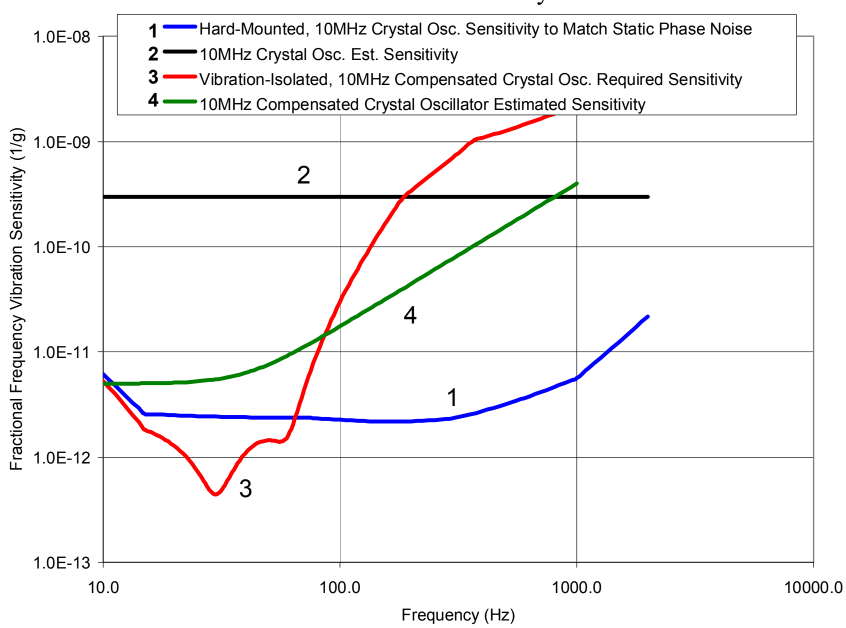

Figure 2. Required Vibration Sensitivity to Match Vibration-Isolated 10MHz Oscillator Static Phase Noise

II. VIBRATION IN NON-OSCILLATOR COMPONENTS

Oscillator vibration results in signal frequency modulation (FM) and amplitude modulation (AM). The FM can be a result of vibration-induced changes in: (a) the oscillator resonator resonant frequency or (b) the oscillator loop phase shift. Resonator frequency changes (for a crystal resonator) are a result of vibration-induced stress on the quartz blank. Loop phase changes can be induced by relative movement in the oscillator enclosure cover, printed wiring board, and non-resonator loop components. The AM can be a result of vibration-induced changes that affect the oscillator loop signal path gain. In general, vibration-induced AM is a lesser concern because it can be suppressed by employing gain compression/limiting in both the oscillator and non-oscillator signal path circuitry.

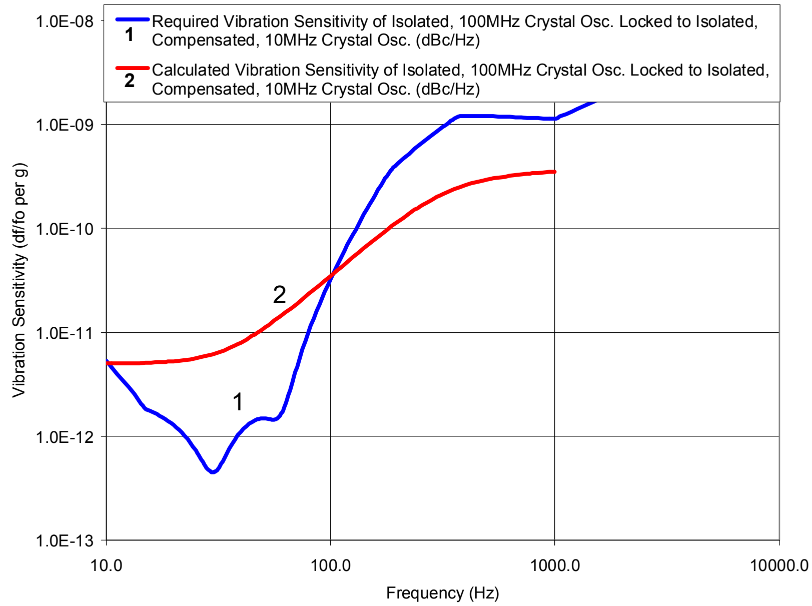

Figure 3. Required vs. Calculated Vibration Sensitivity for a 100MHz Crystal Oscillator Phase-locked to an Accelerometer-Compensated, 10MHz Crystal Oscillator with Both Mounted on Two Stages of Vibration Isolation

Vibration in non-oscillator components and subassemblies results in signal phase modulation (PM). Components identified as having high relative [phase] sensitivity to vibration include coaxial cables and connectors, narrow-bandwidth filters, RF assembly enclosure covers, and printed wiring board assemblies. Even when these components are subjected to vibration-isolation, vibration can induce signal phase modulation (usually above several hundred Hz carrier offset frequency) whose sideband spectral level exceeds that due to oscillator vibration. Figure 4 shows the required vibration [phase] sensitivity that would be required in each of ten, signal path, non-oscillator components mounted in either vibration-isolated or non-isolated assemblies that would result in the same degree of phase noise as occurs in the vibrating crystal oscillator arrangement of Figure 3. Also shown in Figure 4 is the typical sensitivity to vibration of a single coaxial cable with connectors, measured at VHF. Note that if/when such a coaxial cable were to be used to carry a signal between a vibration-isolated to a non-isolated assembly, spectral degradation would occur at carrier offset [vibration] frequencies above 100Hz.

Vibration in band-pass filters containing air-core inductors can produce significant spectral degradation. Figure 5 shows measured results for a vendor filter where the filter inductors were poorly-staked, well-staked, and fully foamed. Note that mechanical non-linearity (enameled wire, coil turns hitting or rubbing against one another) resulted in phase noise degradation out to 8kHz, well in excess of the maximum vibration input frequency.
Intermittent contact has been observed to result in signal spectral degradation out to offset frequencies in the 100kHz range. This can be the result of loose particles from machining or galling, loose parts from assembly (ie, washers, etc.), bond wires or cables, covers, and poorly secured subassemblies. Collisions occur when relative motion in piece parts exceeds the space between them. Thus, it is best to avoid unconstrained contact between parts.

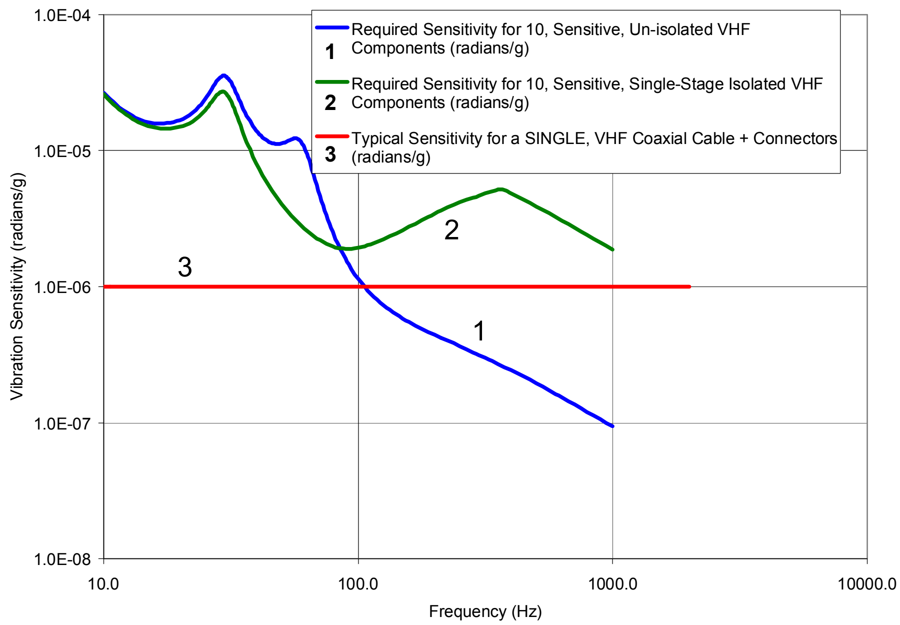

Figure 4. Required [Phase] Sensitivity to Vibration in Non-Oscillator Components

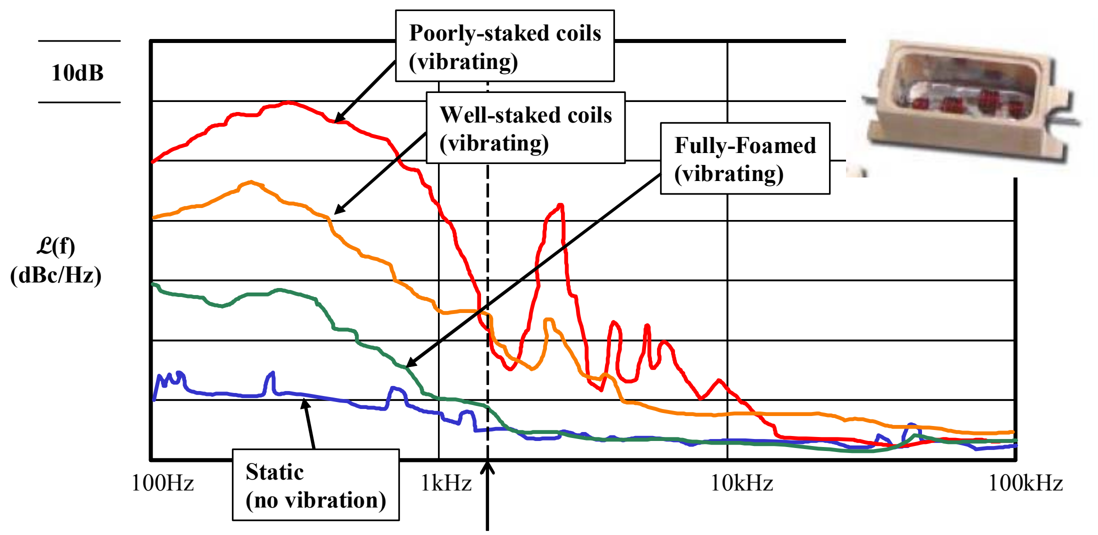

Figure 5. Residual Phase Noise Under Vibration for a Vendor L-C Filter

PHASE NOISE MEASUREMENTS

Accurately interpreting phase noise under vibration measurement results, as well as isolating vibration related problems to specific subassemblies and components, can be arduous. Some of the things that can result in inaccurate assessment of hardware performance include the following:

1. Improperly secured coaxial cables and connectors between the UUT on the shaker and the measurement equipment. [Coaxial cables should be secured at the UUT fixture to minimize relative motion between the cable and the cable connector. Plenty of "slack" should be used in the cable run. A residual phase noise test can be made with the UUT replaced by a through-line to verify the integrity (under vibration) of the connections to and from the shaker.]
2. UUT and measurement apparatus sensitivity to acoustic noise (blowers, fans) in the vibration test area. [A UUT phase noise measurement can be conducted with the UUT suspended slightly off the shake table with shaker, blowers, etc on to check UUT and measurement apparatus sensitivity to acoustic stress.]

3. UUT sensitivity to shaker magnetic field. [This effect can sometimes be evaluated by re-measurement of UUT phase noise under vibration with the distance between the UUT and shaker head increased. Use of a horizontal slide plate accommodates this test procedure.]
4. Incidental off-axis vibration and UUT vibration outside the prescribed vibration profile frequency range. [These can be measured using accelerometers.]
5. Improperly secured subassemblies and unexpectedly sensitive components in the UUT. [This type of problem can often be isolated via visual inspection, extraction and phase noise measurement of specific subassembly signals, and localized vibration while operating the phase noise measurement apparatus in the real-time mode. In addition, display of the detected noise, referred to base-band as a voltage vs. time waveform may add insight as to the nature of the problem, especially in the case of impulsive noise resulting from loose (colliding) surfaces.]
6. Inaccurate display of phase noise levels by the Phase Noise Measurement System. [Vibration can induce phase noise spectra that include relatively narrow bandwidth peaks (mechanical resonances) and rapidly changing levels (input vibration power spectral density spectra). Most Phase Noise Measurement Systems make provision for user-selectable measurement bandwidths. If un-necessarily large measurement bandwidths are selected, the amplitude and shape of a noise peak may be inaccurately displayed. In addition, the Measurement System software may erroneously interpret a finite bandwidth noise peak as a "zero bandwidth" discrete signal and report it's amplitude incorrectly. Usually these discrete signals are separately characterized as color-coded or dashed lines in the display and separate column data in the data file.]

Since vibration does not induce discrete noise sidebands, the appropriate correction factor should be applied. Some of these effects are characterized in Figure 6. As shown in the figure, the Noise Measurement System default and/or user-selected measurement bandwidths usually increase with increasing measurement frequency. This is usually done to reduce measurement time and limit the number of data points that needed to be saved. As a result, a vibration-induced noise peak (at 1kHz in the figure) and acoustically-induced noise peak (3kHz) are measured in 10Hz and 100Hz bandwidths, respectively. The software erroneously identifies these as zero-bandwidth discrete sidebands. As a result, their amplitude is not reduced (as it should be) when displaying the data on a dBc/Hz bandwidth basis. Note also that the discrete signal at 18kHz is not even detected because of the large (300Hz) measurement bandwidth.

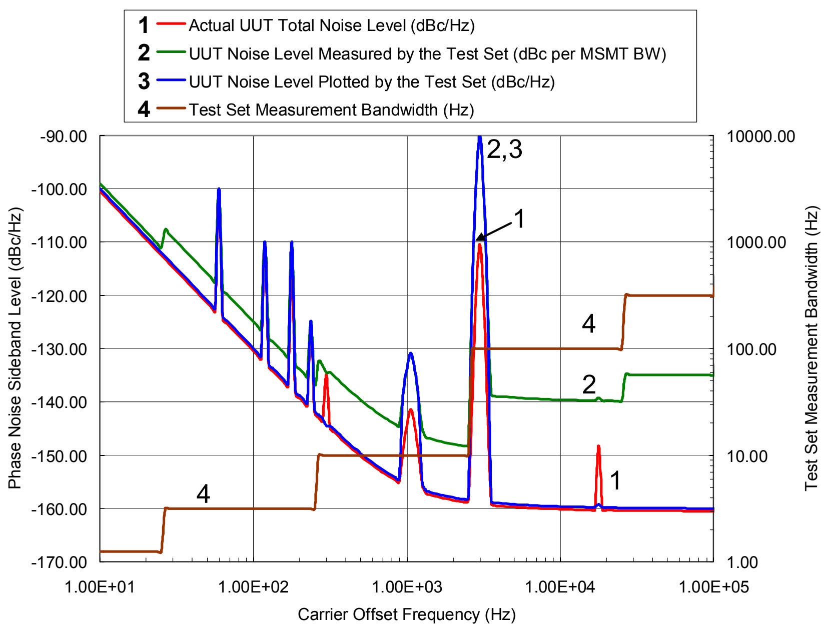

Figure 6. A Comparison of Actual vs. Test Set Measured vs. Test Set Displayed Phase Noise

MINIMIZING VIBRATION-INDUCED PHASE NOISE

The following guidelines constitute the authors recommendations for designing non-oscillator, RF signal processing hardware for acceptably low levels of (phase) sensitivity to vibration:

1. Components which require adjustment should be avoided or cemented after tuning.
2. Avoid non-potted inductors.
3. When laying out circuits, avoid very high circuit impedances sensitive to capacitance variation due to cover motion.
4. Ensure hut and module covers are sufficiently stiff.
5. Avoid use of unnecessarily narrow bandwidth (high group delay) filters.
6. Provide clamping to coaxial cables.

In addition, the following is a general "checklist" for designers:

- ❑ Obtain or generate a specification for "allowable" levels of phase noise.
- ❑ Sub-allocate to signal path circuitry.
- ❑ Identify and obtain sensitivities for components with historical vibration and acoustic stress sensitivity.
- ❑ Perform sensitivity tests on unevaluated components.
- ❑ Update sub-allocation based on test data.
- ❑ Incorporate use of vibration isolation or vibration cancellation where required.
- ❑ If specified performance still cannot be met, seek and evaluate use of alternate architectures and components.

CONCLUSIONS

Crystal resonator and oscillator frequency sensitivity to vibration have improved to a point where the phase sensitivity of non-oscillator components cannot be ignored. Of particular concern are sensitive components such as coaxial cables and connectors and narrow band filters. In addition, mechanical resonances and non-linearity can results in significant signal spectral degradation in the presence of vibration and acoustic stress. Guidelines have been established and described for minimizing residual noise degradation in non-oscillator components and assemblies due to vibration and for identifying and isolating difficulties associated with performing phase noise under vibration testing.

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