Vibration-Induced Phase Noise

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“We have met the enemy, and it is vibration.”

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Acknowledgements

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  - For material reproduced from our co-authored Tutorial "Vibration-Induced Phase Noise in Signal Generation Hardware" presented at the 2009 RFTF/IFCS Conference in Besancon, France.
- Frequency Electronics, Incorporated
  - For vibration laboratory photographs and vibration-induced phase noise measurement result plots.

Tutorial Objectives – That attendees be able to:

- Identify the sources of vibration-induced phase noise and seemingly discrete spurious signals in components and circuit assemblies.
- Translate between the different methods of specifying vibration sensitivity and allowable levels of vibration in components and electronic assemblies.
- Sub-allocate phase noise and vibration sensitivity requirements to subassemblies to guide design decisions.
- Evaluate the vibration sensitivity and vibration-induced phase noise of oscillator and non-oscillator components and signal generation circuit assemblies. Be aware of techniques for reducing the vibration sensitivity.
- Become familiar with vibration sensitivity and vibration-induced phase noise measurement methods and troubleshooting techniques.

Tutorial Topics

- Introduction
- Part I: Vibration-Induced Phase Noise Analysis
  - Section 1: Review of Phase Noise Metrology, Performance, and Measurement Techniques.
  - Section 2: Vibration Induced Phase Noise
  - Section 3: Vibration Sensitivity: Typical Values and Improvement Techniques
- Part II: Vibration Induced Phase Noise Measurement Methods and Troubleshooting Techniques
  - Section 1: Measurement Methods by Type of Assembly (Oscillators, Non-oscillator components, and Multifunction Assemblies
  - Section 2: Data Distortion Issues
  - Section 3: Troubleshooting Techniques

Introduction

- Why is Phase Noise and Vibration-Induced "Phase Noise" so important?

  - Phase noise or time jitter has a direct impact on the performance of communication and radar systems.

  - Vibration is most often a significant source of additional signal phase noise degradation that limits system performance.

  - Both static and vibration-induced phase noise or phase modulation (PM) noise is the more significant contributor to signal spectral degradation, compared to amplitude modulation (AM) noise because:
    (1) PM noise level is subject to significant increase as a signal is subjected to frequency multiplication, and
    (2) AM noise tends to be suppressed when the various RF signals pass through amplification stages operated in gain compression.

Part I: Vibration-Induced Phase Noise Analysis

Section 1:

Review of Phase Noise Metrology, Performance, and Measurement Techniques

Origins of Static Noise in components

- Noise Defined
  - Noise is a random phenomena that obscures an electrical signal.
- Sources of Noise
  - Sources of electrical noise typically occur at the “atomic” level and include:
    - shot noise
    - thermal noise
    - generation-recombination or flicker noise
    - Random walk noise
  - Shot noise in electronic devices results from unavoidable random statistical fluctuations of the electric current when the charge carriers (such as electrons) traverse a gap. The current is a flow of discrete charges, and the fluctuation in the arrivals of those charges creates shot noise. $I_n^2=2qI\Delta B$

Origins of Static Noise in components

- Thermal noise, or Johnson noise) is generated by the random thermal motion of charge carriers (usually electrons), inside an electrical conductor, which happens regardless of any applied voltage. $V_n^2=4kTB\Delta f$
- Generation-recombination flicker noise or 1/f noise, characterized by a 1/f power spectrum
- Random walk noise (usually characterized by a 40dB/decade slope in oscillators) occurs very close to the carrier and appears to often be related to environmentally induced, random variations

- Other sources of noise include carrier signal noise modulation caused by DC supply or voltage regulator noise acting on a RF device having gain and phase sensitivity to DC supply variation.

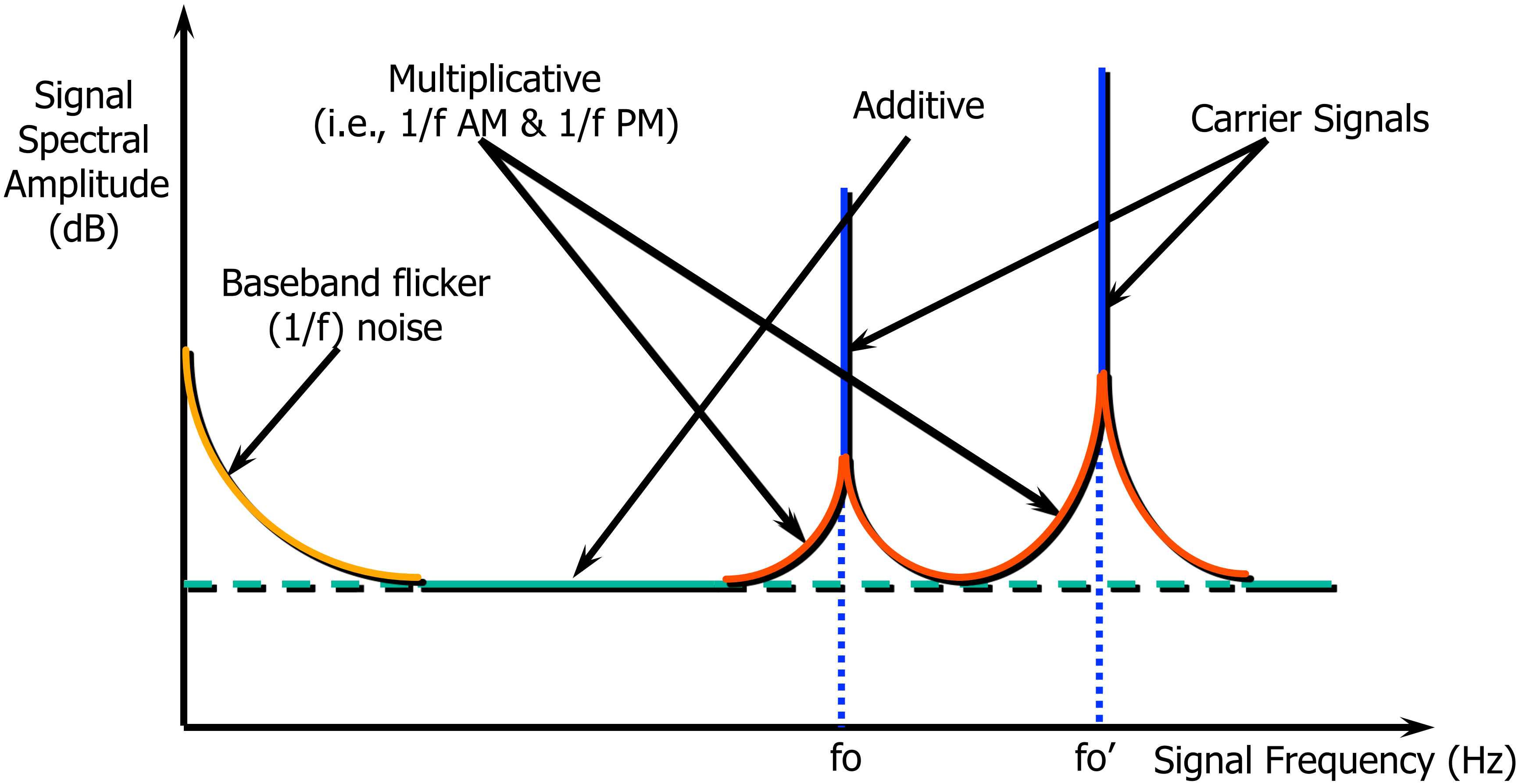
Types of Phase Noise

- Additive Noise: Noise that exists "in addition" to the carrier signal and who's amplitude is <u>independent</u> of the carrier signal level.
  - Additive noise normally occurs as white (constant level) noise.
  - Thermal noise or "KTB" noise power = -174dBm/Hz (½ AM noise and ½ PM noise).

- Multiplicative Noise: Noise that exists at base-band, and that modulates the carrier signal by means of a non-linearity or via device phase or frequency sensitivity to the baseband excitation.
  - Multiplicative noise level is <u>not</u> independent of the carrier signal level.
  - Multiplicative noise often occurs as flicker (1/f) noise.
  - Phase noise modulation additionally results from baseband noise from DC power supplies or voltage regulators and noise modulation of semiconductor junction capacitance.

- Vibration-induced phase noise results from device or signal path frequency or phase sensitivity to dimensional movement and stress. This is a carrier signal modulation effect also.

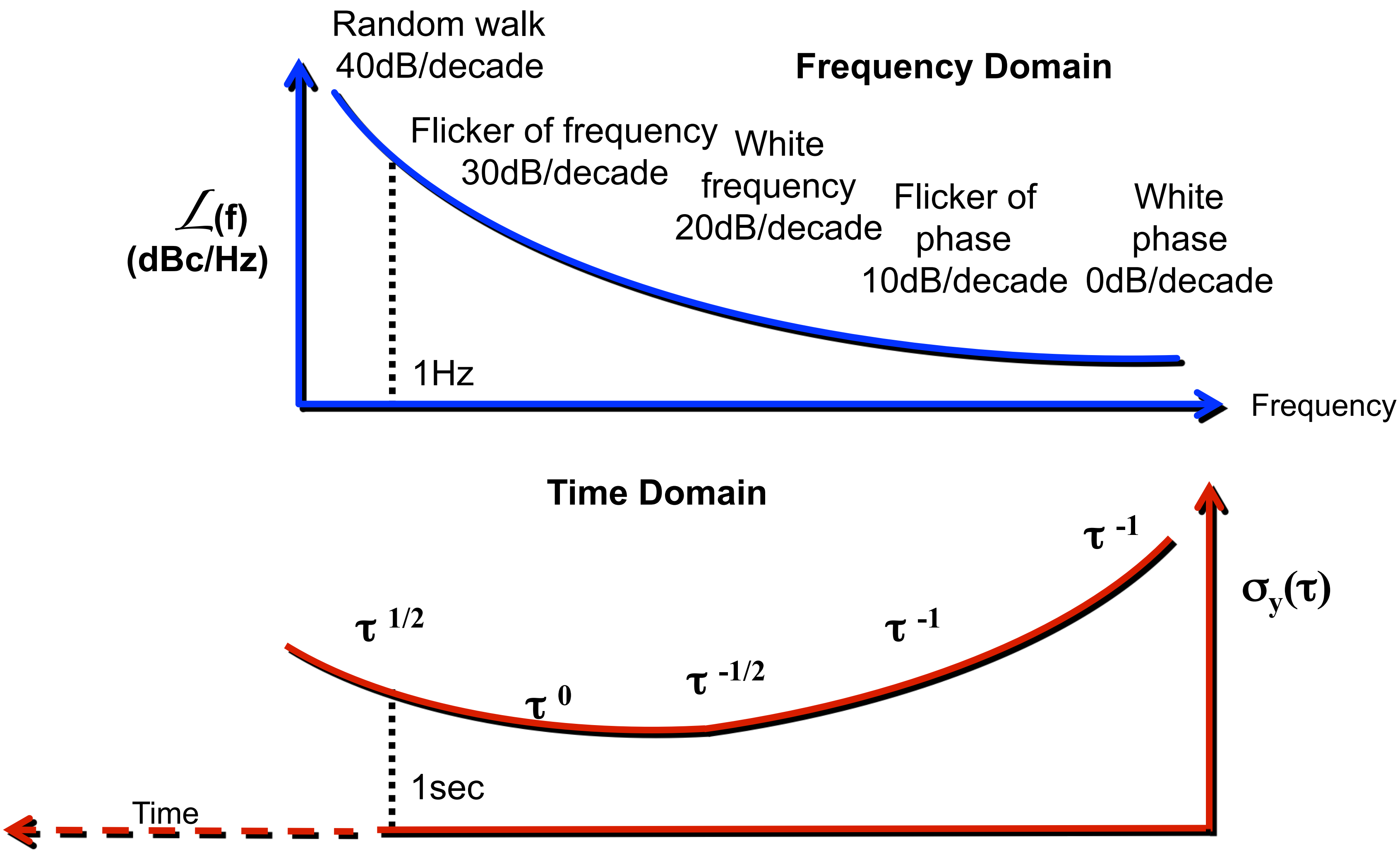
Multiplicative vs. Additive Static Phase Noise



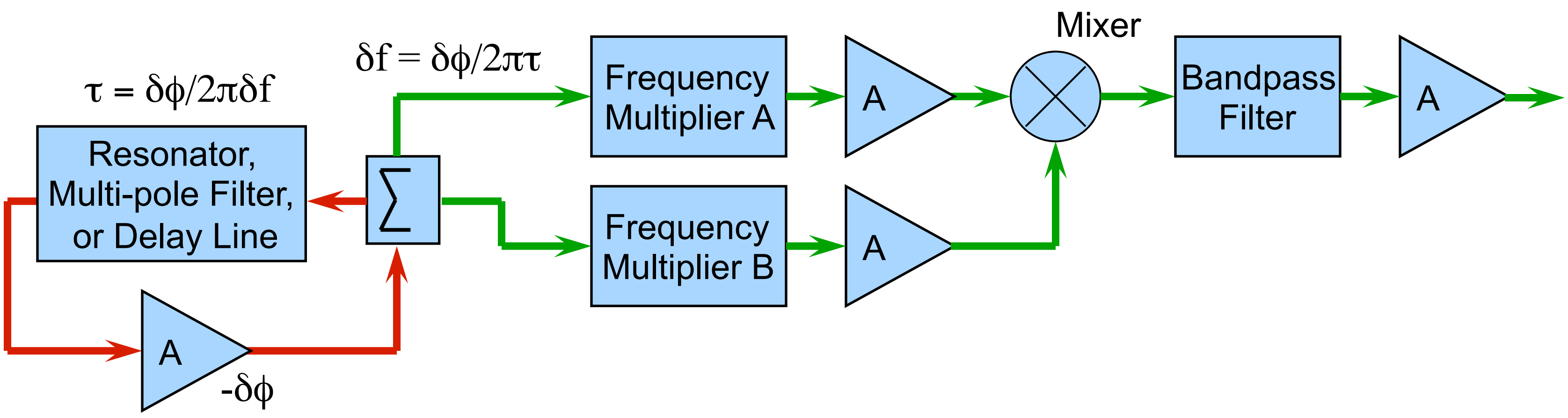
Frequency/Phase Stability can be Specified in the Frequency or Time Domain

- Frequency Domain:
  - $S_\phi(f)$ = Power spectral density of the phase fluctuations (rad^2/Hz).
  - $S_y(f)$ = Power spectral Density of the fractional frequency fluctuations (1/Hz).
  - $S_y(f) = 2(f/\nu_o)S_\phi(f)$, ν_o = carrier frequency.
  - $\mathcal{L}(f) = S_\phi(f)/2$.
  - For small modulation indices, $\mathcal{L}(f)$ = single sideband phase noise-to-carrier power ratio, in a 1Hz bandwidth, at a offset frequency f from the carrier (dBc/Hz).
- Time Domain:
  - The two sample deviation, or square root of the Allan Variance is the standard method of describing the short-term stability of oscillators in the time domain. It is usually denoted by $\sigma_Y(\tau)$.
- Vibration-induced phase noise is normally specified, measured, and plotted in the frequency domain.

Types of Phase Noise Spectra



Signal Path Phase Noise Contributors



Absolute noise refers to noise in an oscillator output signal. **Frequency** instabilities in the oscillator frequency control element (i.e., resonator) and **Phase** instabilities in the oscillator loop components (i.e., sustaining stage amplifier) result in signal **Frequency** instability.

Residual noise refers to noise in non-oscillator, signal path components that modulate the signal **Phase** and **Amplitude**, but not the signal **Frequency**.

Sometimes residual noise is referred to as "additive" noise. This makes it difficult to discriminate between it and KTBF-type additive noise.

Part II: Vibration Induced Phase Noise Testing

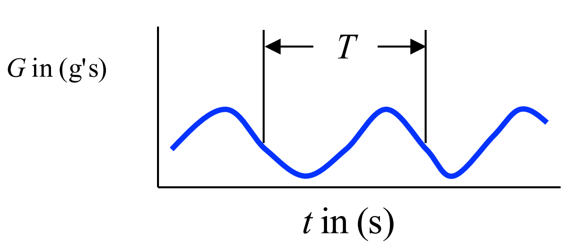
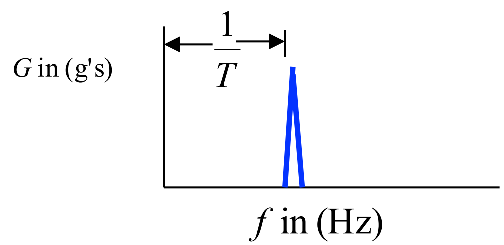
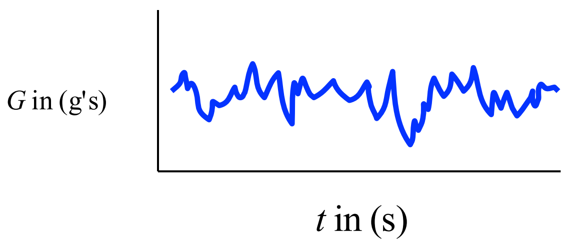
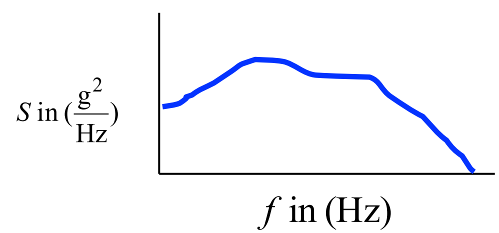
Section 2:

Vibration Testing

Vibration Terminology

- Displacement, x, in m
- Velocity, v, in m/s
- Acceleration, a, in m/s^2
- Normalized acceleration, G=(a/g)
  - g=9.81 m/s^2 (earth's gravity)
- At a particular frequency, f, in Hz
  - $|a|=(2\pi f)^2|x|$
  - $|v|=(2\pi f)\ |x|$
- Force, $F=ma$, in N
  - Weight, $w=mg$
- Mass, $m=w/g$, in kg
- Stiffness, k in N/m
- Natural Frequency, f_n, in Hz
  - System naturally wants to vibrate
  - ≈System responds maximally when excited
- Damping
  - Quality factor (sharpness-of-resonance), $Q=f_n/\Delta f_{hp}$
  - Viscous damping factor, $c = F/v$, in N-s/m
    - Critical damping, $c_c=4\pi m f_n$
    - Fraction of critical damping, $\zeta=c/c_c=1/(2Q)$

Broadband vs. Narrowband (Seemingly Discrete) Vibration

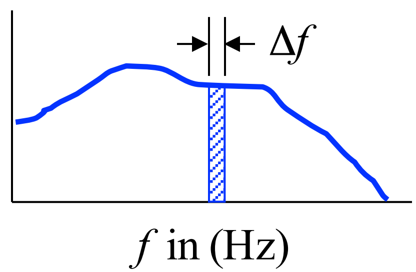
	Time Domain	Frequency Domain	Peak Amplitude
Near-Discrete			$\sqrt{2}\cdot$RMS
Broadband			$\approx 3\cdot$RMS

"Seemingly discrete" because even vibration from engines, rotors, etc. have larger spectral bandwidths, compared to discrete, CW electrical signals.

Vibration Power Spectral Density $S_g(f)$

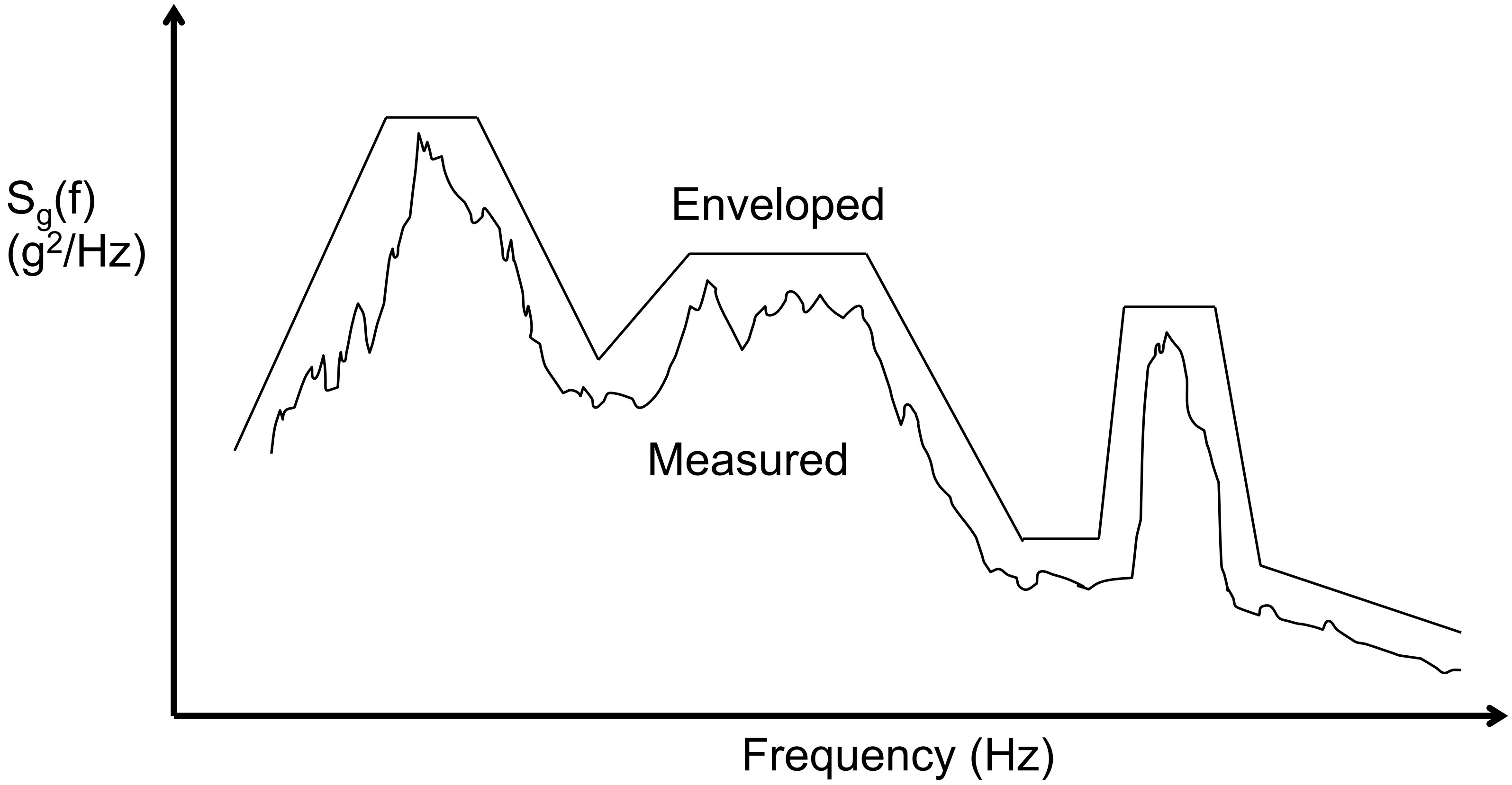
- The amplitude of broadband vibration at a particular frequency is a meaningless.
- The power of the vibration in an arbitrary band of frequencies (bandwidth) is meaningful.

$$S = \frac{G_{RMS}^2}{\Delta f} \text{ in } \left(\frac{g^2}{\text{Hz}}\right)$$



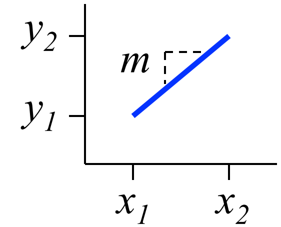
- Use units that are proportional to power (amplitude squared)
- Divide power by bandwidth to form density in order to make specification of bandwidth unnecessary
- $S_g(f)$ (g^2/Hz) is analogous to power spectral density of phase fluctuations, $S_\phi(f)$ (rad^2/Hz).

Often, specified vibration test PSDs are derived by enveloping measured data.



Logarithmic Interpolation

- Vibration PSD levels are often specified by enveloping measured or calculated vibration levels with straight line segments. The resulting PSD is specified as sloping lines on log-log PSD plots given in terms of “dB/octave” or “dB/decade”.



- The amplitude at any point can be obtained from:

$$\frac{y_2}{y_1} = \left(\frac{x_2}{x_1}\right)^{\frac{m}{n}}$$

- Where *m* is the signed slope, and *n* is given by:
  - 3 if *m* given in dB/octave (most common)
  - 10 if *m* given in dB/decade

$$m = n\frac{\log\left(\frac{y_2}{y_1}\right)}{\log\left(\frac{x_2}{x_1}\right)}$$

- If the endpoints are given and an intermediate point is desired then first calculate the slope
- Then use

$$y = 10^{\left(\log y_1 - \frac{m}{n}\log x_1\right)} x^{\frac{m}{n}}$$

- to calculate the intermediate point.

Sources of Vibration-Induced Phase Noise

Components

- Transmission lines and connectors
- Air-core inductors
- Filters
- Printed wiring boards
- Enclosure covers
- Jumper and bond wires
- Misc. non-cemented components (i.e., ferrite beads)
- Non-resonator components in the Oscillator loop
- The Oscillator frequency-determining element (i.e., the resonator

Mechanisms

- Dimensional change
- Mechanical strain
- Intermittent contact
- Electromagnetic field strength variation

Fractional Frequency Vibration Sensitivity

- Most work in the field of vibration-induced phase noise has been focused on oscillators – the most sensitive component at near-carrier offset frequencies.

- *Fractional frequency sensitivity* is the appropriate measure of oscillator and oscillator resonator vibration sensitivity and is obtained by measuring the change in oscillator fractional frequency under vibration.

$$\Gamma_f = \frac{\Delta f_0}{f_0 G}$$

  - where Δf_o is the vibration-induced carrier frequency change in Hz

- Fractional frequency sensitivity tends to be constant over vibration frequency except for mechanical resonances.

- The fractional frequency sensitivity is a function of vibration frequency, direction, and temperature.

Phase Sensitivity to Vibration

- For non-oscillator components, vibration causes phase error directly and the sensitivity could be called *phase sensitivity to vibration.*

- Depending upon which results in the most constant value over vibration frequency, the best measure of sensitivity could be
  - phase error per acceleration $$\Gamma_{\phi} = \frac{\Delta\phi}{G}$$
  - phase error per velocity $$\Gamma_{\phi v} = \frac{\Delta\phi}{v}$$
  - phase error per displacement $$\Gamma_{\phi x} = \frac{\Delta\phi}{x}$$

- For the sake of comparison, a non-oscillator component can be described as having an equivalent fractional frequency sensitivity

$$\Gamma_f = \frac{\Gamma_{\phi} f}{f_0}$$

Allowable Level of Vibration

- Solving for acceleration:

$$G_{RMS} = \frac{\Delta f_{0\,RMS}}{f_0 \Gamma_f} = \frac{f \Delta\phi_{RMS}}{f_0 \Gamma_f} = \frac{f\sqrt{S_\phi \Delta f}}{f_0 \Gamma_f} = \frac{\sqrt{S_\phi \Delta f}}{\Gamma_\phi}$$

- Which can be used to determine the maximum allowable discrete vibration, in which case:

$$G = \sqrt{2} G_{RMS}$$

- If the vibration is broadband, the maximum allowable broadband vibration is:

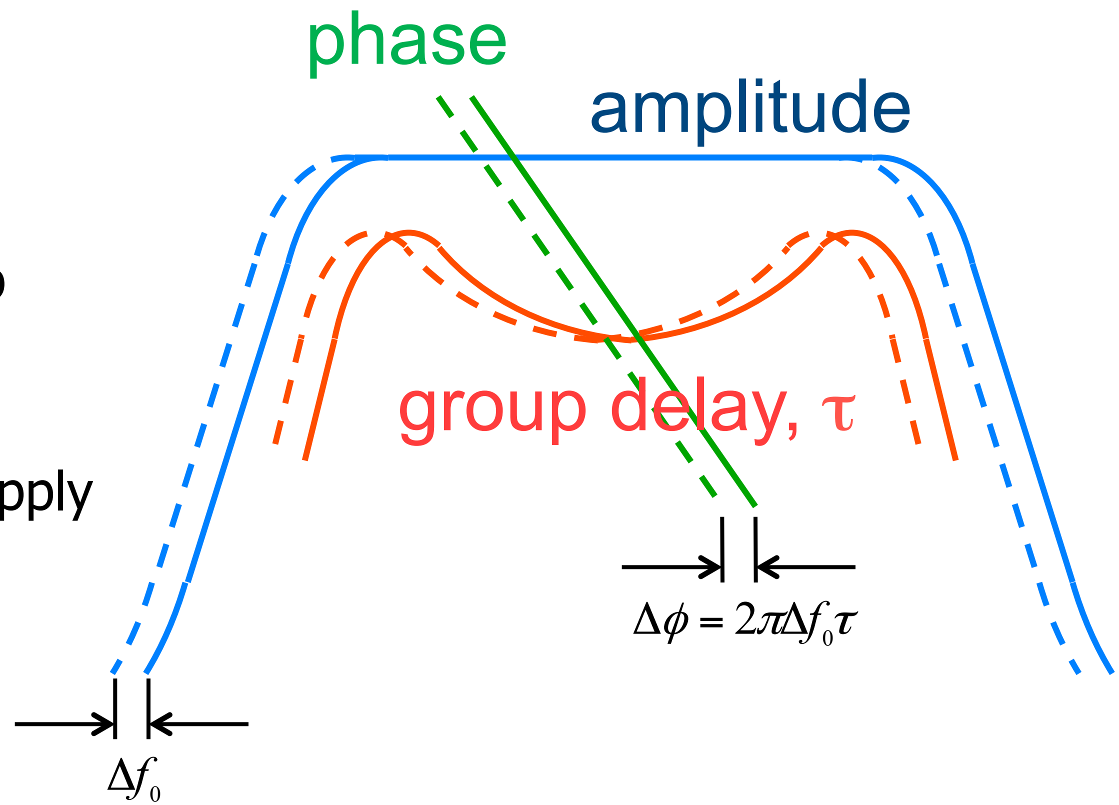
$$S_g = \frac{G_{RMS}^2}{\Delta f} = \frac{f^2 S_\phi}{f_0^2 \Gamma_f^2} = \frac{S_\phi}{\Gamma_\phi^2}$$

Filter Vibration Sensitivity

- Filters can either be characterized in terms of fractional (center) frequency sensitivity to vibration or phase sensitivity to vibration.
- In the latter case

$$\Gamma_\phi = 2\pi f_0 \tau \Gamma_f$$

- where τ is the filter group delay in seconds*
- The previous equations apply



* For a given value of Γ_f, narrowband (large delay) filters exhibit higher phase sensitivity to vibration.

Intermittent Contact (Mechanical Non-linearity)

- Collisions can cause noise on
  - signals
  - power
  - ground
  - or they can cause unexpected impulsive vibration
- Possible causes
  - loose particles from machining or galling
  - loose parts from assembly, i.e. washers
  - lightly sprung electromechanical relays
  - bond wires
  - unconstrained or bundled cables
  - Covers
  - Lack of flatness in bolted down subassembly base vs. chassis
- Vibration-induced phase noise degradation bandwidth due to intermittent contact can be very broadband….well beyond the input vibration bandwidth!

Part I:
Vibration Induced Phase Noise Analysis

Section 3:

Typical Vibration Sensitivity Values and Improvement Techniques

Typical High Q Resonator Vibration Sensitivities

- Oscillator/resonator vibration sensitivity is conventionally expressed on a fractional frequency basis (i.e., $\delta f/f_o$ per g).
- Resonant frequency change in BAW/SAW resonators results from vibration-induced stress on the crystal plate.
- Resonant frequency change in Dielectric microwave resonators results from vibration-induced dimensional change in the resonator assembly.

Quartz Crystal	Parts in 10^{10} to 10^{9} per g
Quartz SAW Resonator	Parts in 10^{9} to 10^{8} per g
Quartz STW Resonator	Parts in 10^{10} to 10^{9} per g
Thin Film Piezoelectric Resonator (FBAR)	Parts in 10^{9} per g
Certain MEMS Resonators	Parts in 10^{11}[1] to 10^{9} per g
Ceramic Dielectric Resonator	Parts in 10^{7} to 10^{8} per g
Whispering Gallery Mode Resonator	Parts in 10^{10} to 10^{9} per g

[1] *Si*Time Application Note AN10032 Rev 1.1 "Shock and Vibration Performance Comparison of MEMS and Quartz-Based Oscillators", February, 2014. Performance is not listed as typical or guaranteed.

Vibration: An Example

- A 100MHz low noise crystal oscillator will typically exhibit a phase noise sideband level 1000Hz from the carrier = -160dBc/Hz
- The corresponding phase instability, $S_\phi(f) = 2X10^{-16}$ rad^2/Hz.
- The corresponding fractional frequency instability is $S_Y(f{=}1000Hz) = 2X10^{-26}$/Hz.
- The crystal resonator vibration PSD level at f=1000Hz that would degrade the at-rest oscillator signal spectrum, based a crystal frequency vibration sensitivity value $\Gamma_f = 5X10^{-10}$/g is extremely small:

$$S_g(f) = S_Y(f)/\Gamma_f^2 = 8X10^{-8}\ g^2/Hz$$

This vibration level is similar to that encountered in an office building!

Methods for Reducing Oscillator/Resonator Vibration-Induced Phase Noise

Least Costly

Vibration isolation of the resonators or of the entire oscillator assembly.

Reduction of resonator vibration sensitivity via resonator design (geometry, mounting, mass loading, etc.).

Use of multiple, unmatched oppositely-oriented devices.

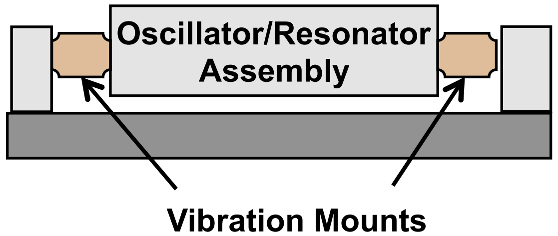
Cancellation via feedback of accelerometer-sensed signals to the oscillator frequency tuning circuitry.

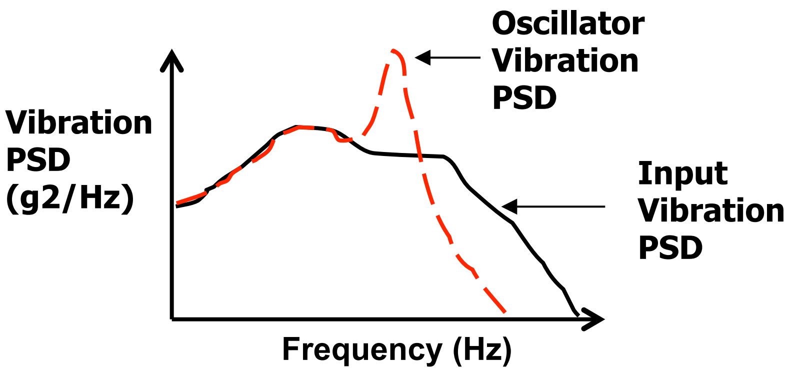
Most Costly

Measurement of individual (crystal) resonator vibration sensitivity magnitude and direction and use of matched, oppositely-oriented devices.

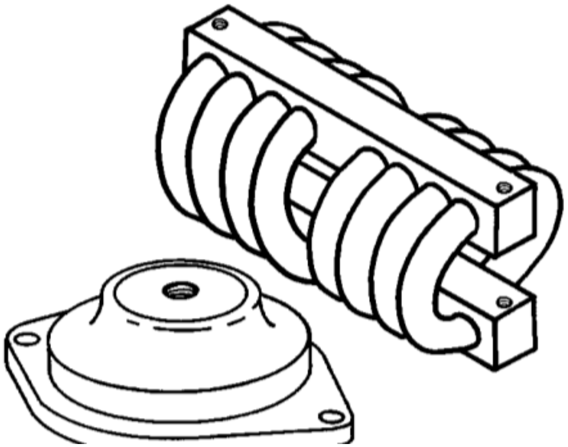
Use of Mechanical Vibration Isolation

- Vibration isolators amplify vibration at a prescribed, resonant frequency and attenuate vibration above the resonant frequency.
- The attenuation response normally rolls off at 20dB/decade.
- In practice, the maximum attenuation is typically lies in the range 25 to 35dB.
- The overall vibration level = area under the curves.
- It is important to properly locate the device C.G. to prevent "rocking" motion.



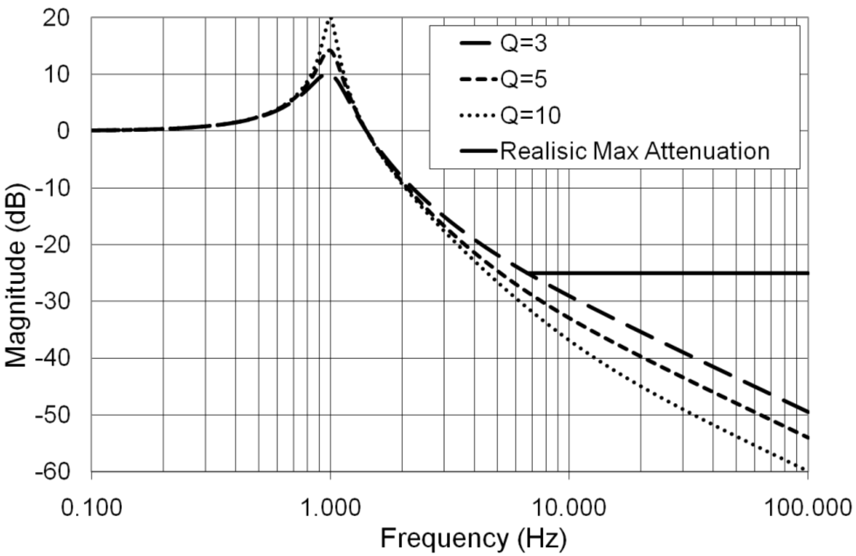


Mechanical Vibration Isolators



(a) (b)

$$T = \sqrt{\frac{1+\left(\frac{f}{f_n Q}\right)^2}{\left[1-\left(\frac{f}{f_n}\right)^2\right]^2+\left(\frac{f}{f_n Q}\right)^2}}$$



Typical vibration isolators for used with acceleration sensitive devices. The resilient element is often:
(a) an elastomer (for lighter assemblies,
or (b) wire rope (for heavier assemblies.

Mechanical Isolation (cont.)

- Absolutely avoid the use of "homemade" isolators.
- Be aware of the relationship between isolator maximum displacement and isolator life, keeping in mind specified device operational, non-operational, and endurance vibration levels.
- Use "bumpers" to prevent excessive isolator displacement, realizing that UUT impact with bumpers will cause impulsive type phase noise.
- An excellent reference is found in "J. Donovan, Vibration Isolation of Acceleration Sensitive Devices, 2011 IEEE International Frequency Control Symposium, May 2011."

Isolator Dimensional Movement Excel Spreadsheet

Assumed Vibration Isolation System Natural Frequency (Hz)	Frequency (Hz)	Relative Transmissibility Squared	MIL-STD-810C Jet Aircraft Vibration PSD (g^2/Hz)	Relative Acceleration PSD (g^2/Hz)	DUT Each-Axis "Differential" Displacement PSD (meters^2/Hz)	Approximate Slice Area Under Curve (cm^2)
63.00	10.00	6.7E-04	7.98E-03	5.33E-06	3.28E-11	
	12.59	1.7E-03	1.00E-02	1.74E-05	4.26E-11	1.24E-06
Assumed Vibration Isolation System Q	15.85	4.6E-03	1.26E-02	5.76E-05	5.62E-11	2.06E-06
5.00	19.95	1.2E-02	1.59E-02	1.97E-04	7.66E-11	3.53E-06
	25.12	3.5E-02	2.00E-02	7.10E-04	1.10E-10	6.37E-06
	31.62	1.1E-01	2.52E-02	2.81E-03	1.73E-10	1.26E-05
	39.81	4.2E-01	3.18E-02	1.34E-02	3.30E-10	3.03E-05
	50.12	2.5E+00	4.00E-02	1.00E-01	9.77E-10	1.13E-04
	63.10	2.5E+01	4.00E-02	1.00E+00	3.90E-09	5.68E-04
	79.43	6.1E+00	4.00E-02	2.46E-01	3.80E-10	6.97E-05
	100.00	2.6E+00	4.00E-02	1.05E-01	6.49E-11	1.50E-05
	125.89	1.7E+00	4.00E-02	6.99E-02	1.72E-11	4.98E-06
	158.49	1.4E+00	4.00E-02	5.59E-02	5.46E-12	2.00E-06
	199.53	1.2E+00	4.00E-02	4.91E-02	1.91E-12	8.79E-07
	251.19	1.1E+00	4.00E-02	4.54E-02	7.03E-13	4.08E-07
	316.23	1.1E+00	4.00E-02	4.33E-02	2.67E-13	1.95E-07
	398.11	1.1E+00	4.00E-02	4.20E-02	1.03E-13	9.47E-08
	501.19	1.0E+00	4.00E-02	4.13E-02	4.03E-14	4.66E-08
	630.96	1.0E+00	4.00E-02	4.08E-02	1.59E-14	2.31E-08
	794.33	1.0E+00	4.00E-02	4.05E-02	6.27E-15	1.15E-08
	1000.00	1.0E+00	4.00E-02	4.03E-02	2.48E-15	5.73E-09
	1258.93	1.0E+00	4.00E-02	4.02E-02	9.86E-16	2.86E-09
	1584.89	1.0E+00	4.00E-02	4.01E-02	3.92E-16	1.43E-09
	1995.26	1.0E+00	4.00E-02	4.01E-02	1.56E-16	-2.77E-09
			1.00E-10			
					Total , Single Axis, RMS Dimensional Change (cm)	**2.88E-02**
33					**Total, Single Axis, Peak Dimensional Change (cm)**	**8.64E-02**

Isolator Dimensional Movement (cont.)

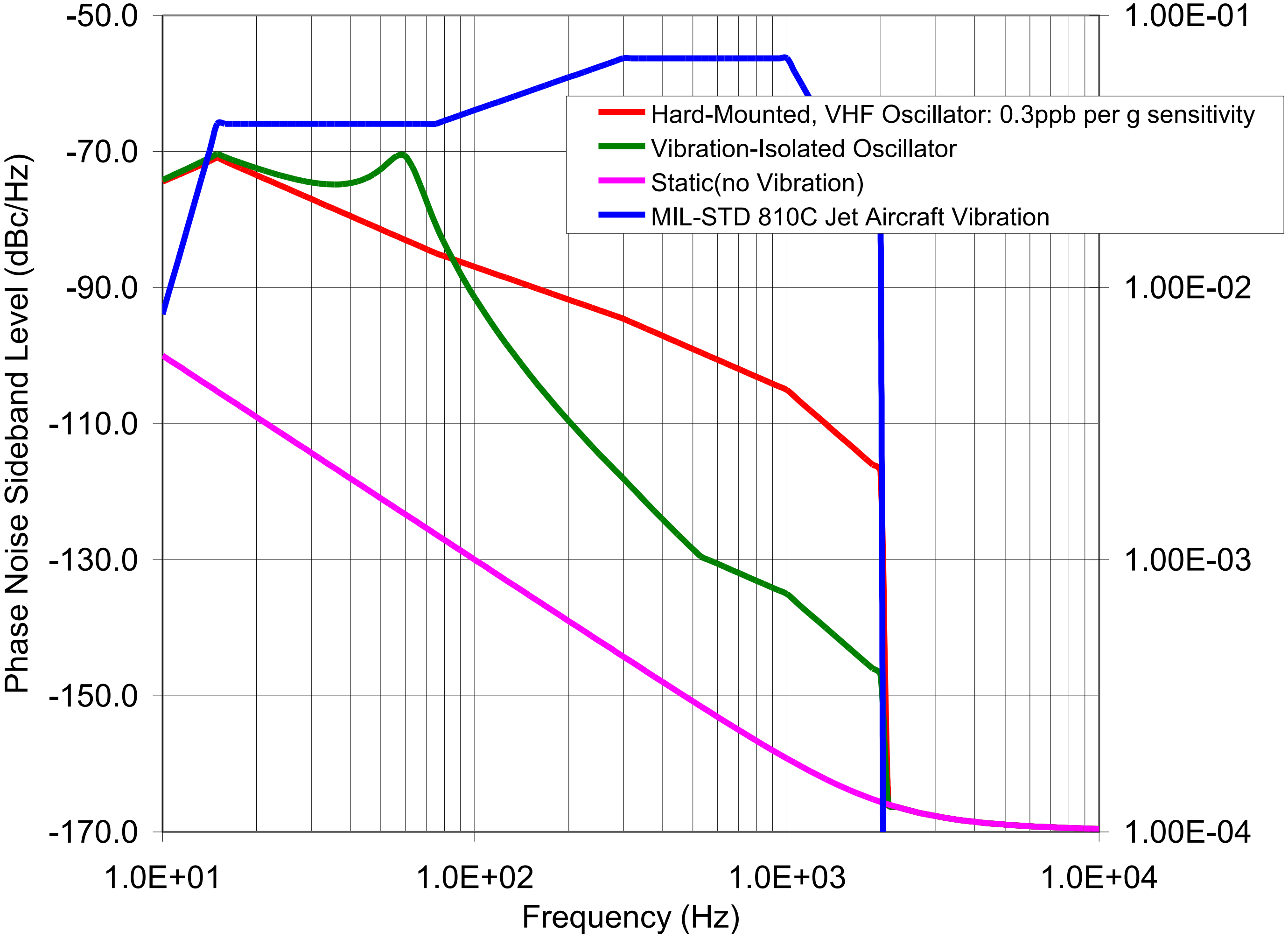
T_R = Relative Transmissibility

$$T_R = \sqrt{\frac{\left(\frac{f}{f_n}\right)^4}{\left[1-\left(\frac{f}{f_n}\right)^2\right]^2+\left(\frac{f}{f_n Q}\right)^2}}$$

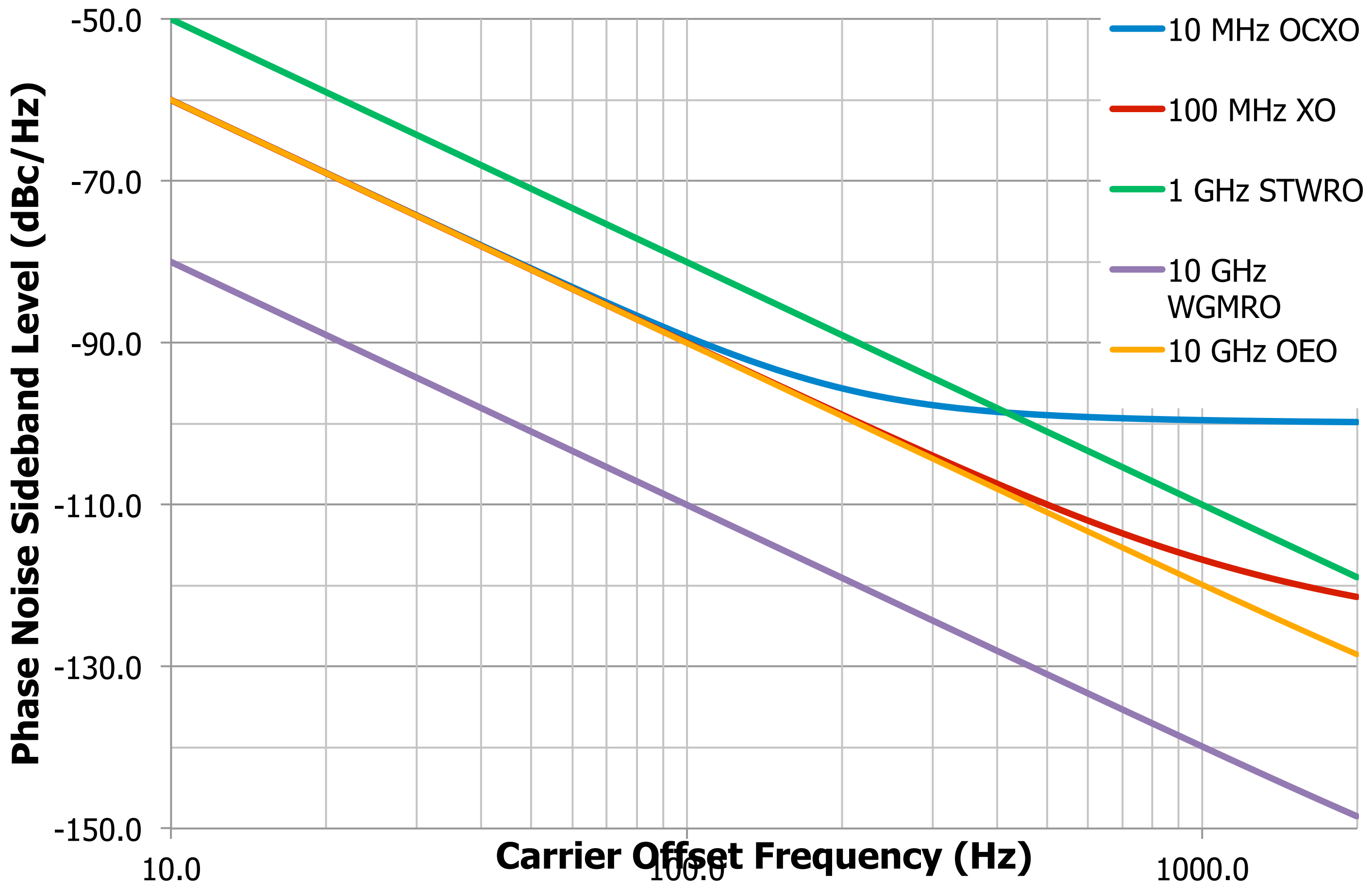
Relative acceleration = $(T_R^2)(Sg_{in}(f))$ in g^2/Hz, $Sg_{in}(f)$ = input vibration PSD.

Differential displacement PSD = $(9.8/(2\pi f)^2)^2$ in meters^2/Hz, where gravitational acceleration = 9.8 meters//second.

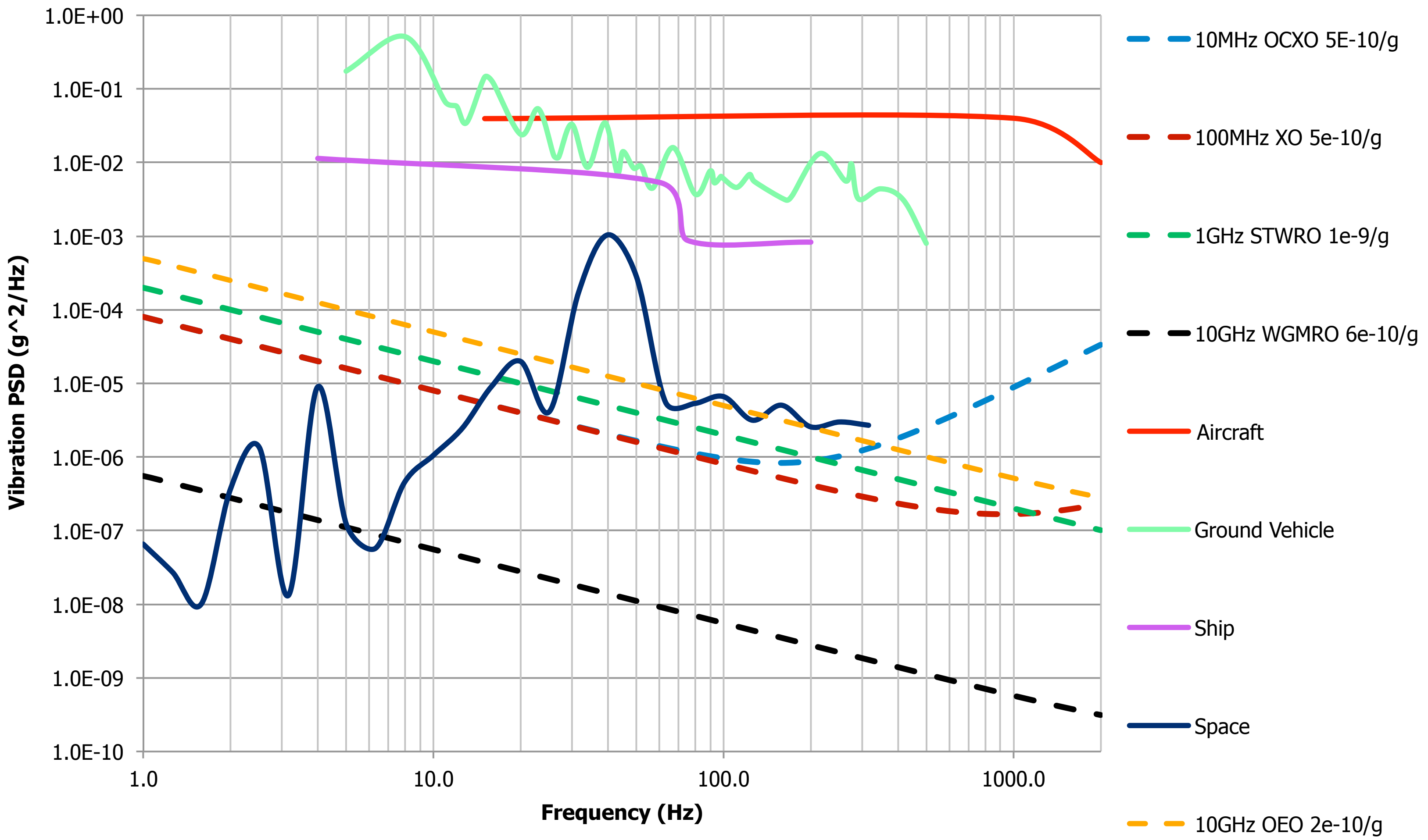
Even with Mechanical Isolation, Vibration-Induced, Oscillator Phase Noise Degradation Remains Substantial



Phase Noise Sideband Level for Various Oscillator Resonator Technologies, All Referred to 10GHz

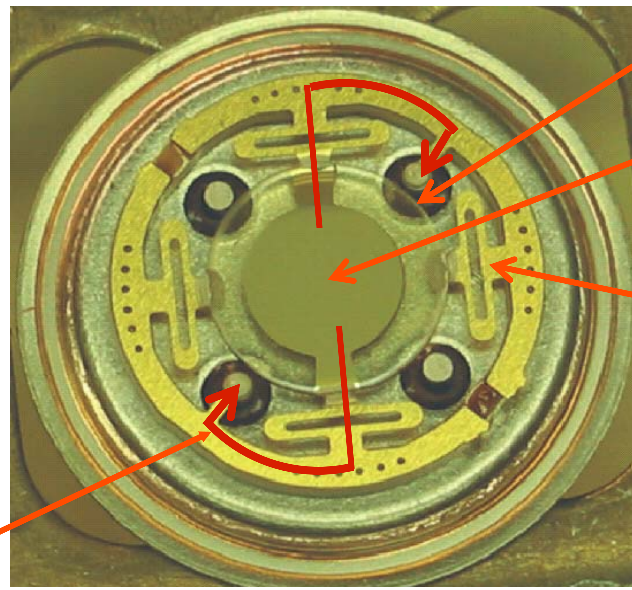


Vibration Levels that would Degrade Oscillator Static Phase Noise by 3dB (static=vibration-induced)



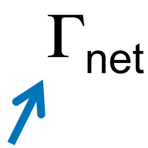
An Example of Vibration Sensitivity Reduction via Resonator Design

- Low stress, QRM (Quad Relief Mounting) crystal resonator mounting scheme [1]

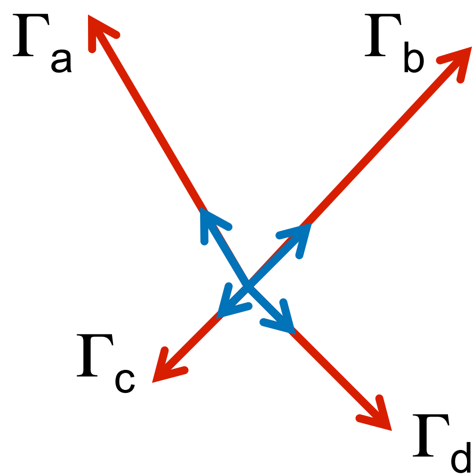


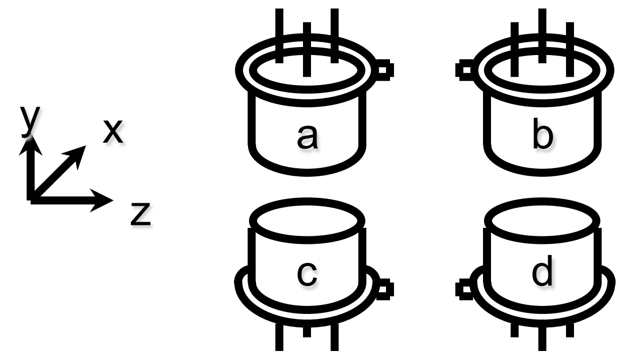
[1] R. B. Haskell, J. E. Buchanan, B. B. Desai, D. Stevens (Vectron International), Y. Kim (U.S. Army Communications-Electronics RDEC), “Acceleration Sensitivity Measurements of Quad Relief Mount Langasite Resonators”, Proc. 2008 IEEE Int’l Freq. Contr. Symp., May, 2008, pp. 237-239.

Use of Multiple Resonators



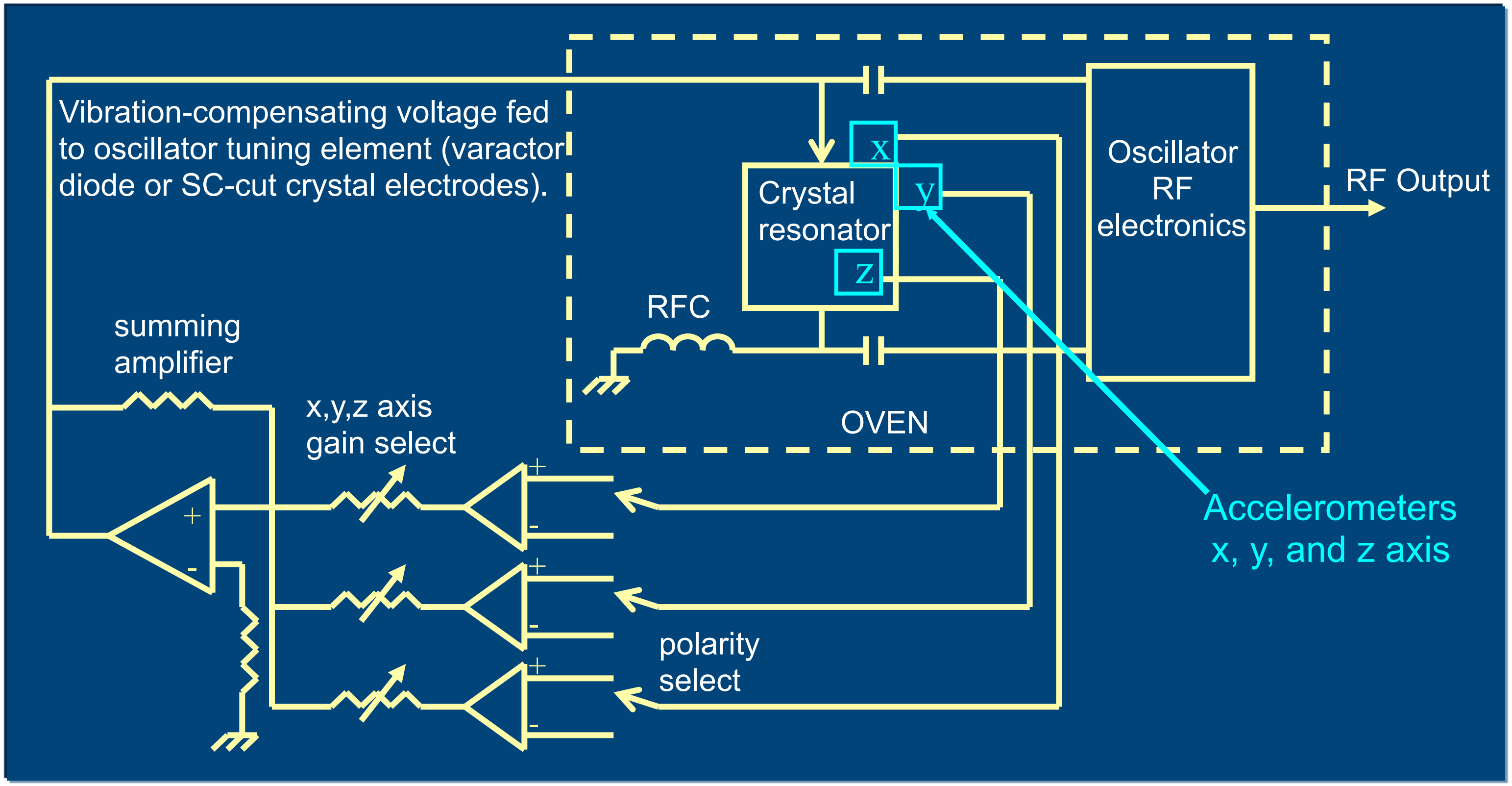
$$\Gamma_{net} = \Gamma_a/4 + \Gamma_b/4 + \Gamma_c/4 + \Gamma_d/4$$





- Series connection of two, unmatched crystals: partial cancellation in z and x directions, no cancellation in y direction. Four, unmatched crystals: partial cancellation in all directions.
- 5:1 reduction in sensitivity typically obtained using four crystals.
- The vibration sensitivity of each crystal can be represented by a vector amplitude and direction.
- The sensitivity of the N, series-connected crystals is the <u>vector</u> sum of each crystal's sensitivity vector divided by N (a frequency change of Δf in one crystal only results in a net frequency change of $\Delta F/N$ for the N series combination.

Cancellation of Vibration-Induced Frequency Change via Electrical Feedback [1]

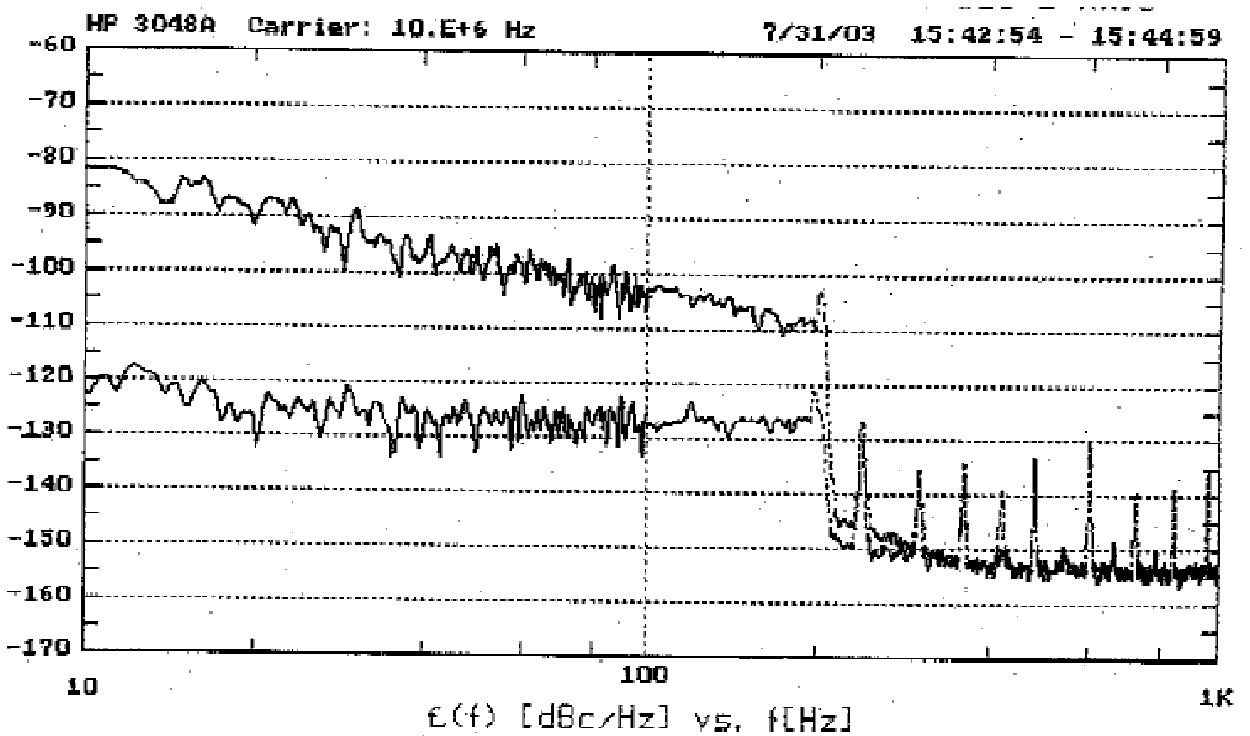


- Vibration produces a voltage from the accelerometers that is appropriately amplified and fed back to the oscillator frequency tune control element.
- Tuning can be via use of varactor tuning diodes or, in the case of an SC-cut crystal, can be applied directly across the crystal electrodes.
- Vibration sensitivity reduction factors of more than 10:1 out to several hundred Hz have been demonstrated in commercially available, 10MHz crystal oscillators.

[1] R. Filler, and V. Rosati, Proc. 25th Annual Freq. Contr. Symp., May, 1981, pp117-121

Performance Improvement in a Frequency Electronics, Inc. 10MHz Crystal Oscillator with Electronic Vibration Cancellation

Measured Results: Input = 0.08g^2/Hz, 10Hz-200Hz

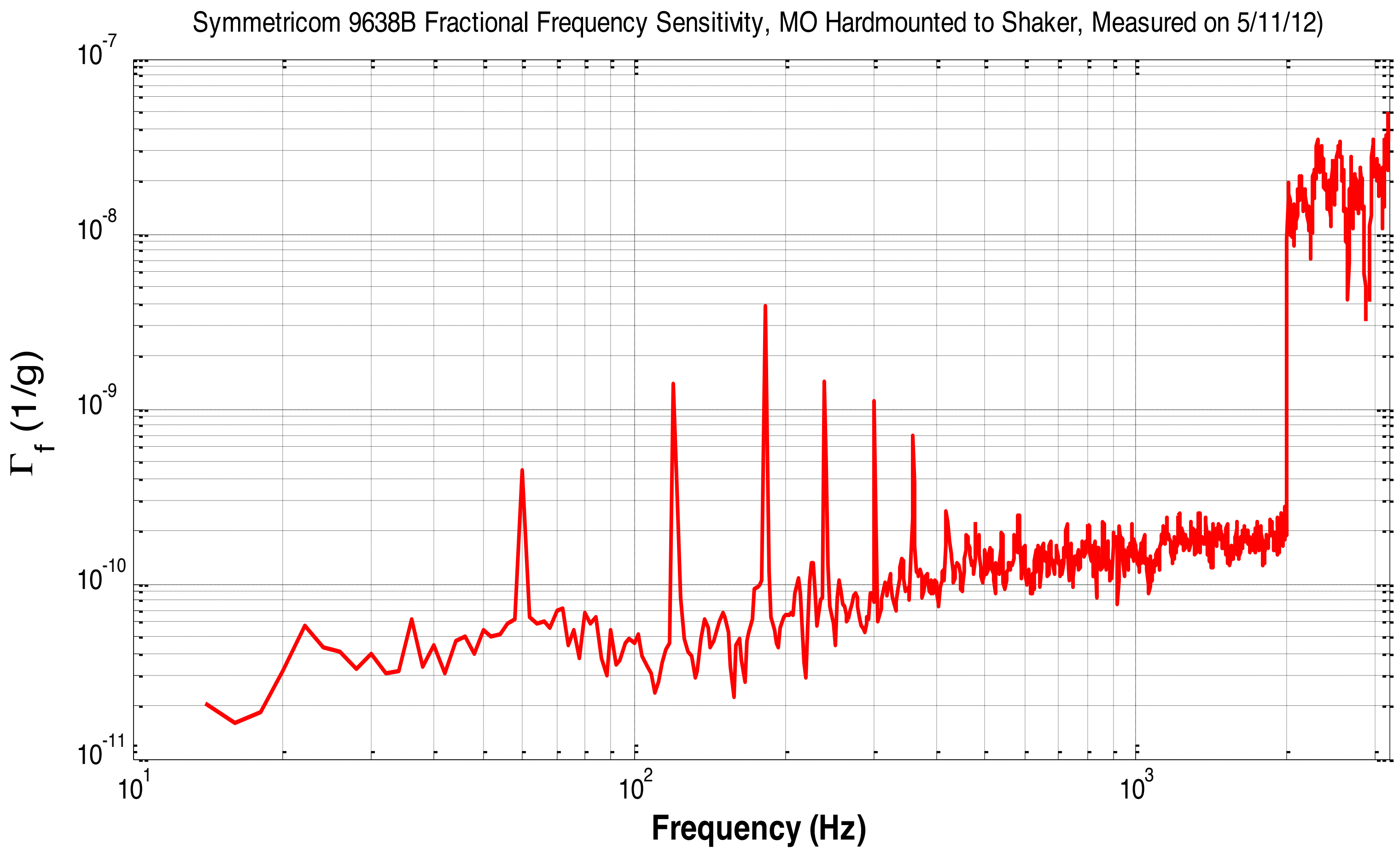


Frequency (Hz)	Standard Performance DUT (upper curve)	Low g-sensitivity DUT (lower curve)
10	$4X10^{-10}$/g	$5X10^{-12}$/g
100	$4X10^{-10}$/g	$2X10^{-11}$/g
200	$3X10^{-10}$/g	$4X10^{-11}$/g

Courtesy of Frequency Electronics, Inc.
http://www.freqelec.com

Measured Performance Improvement in a Symmetricom 10MHz Crystal Oscillator with Electronic Vibration Cancellation

- Vibration input stopped at 2 kHz, so data can be considered valid up to 2 kHz. Discrete signals at multiples of 60 Hz are test equipment-related.

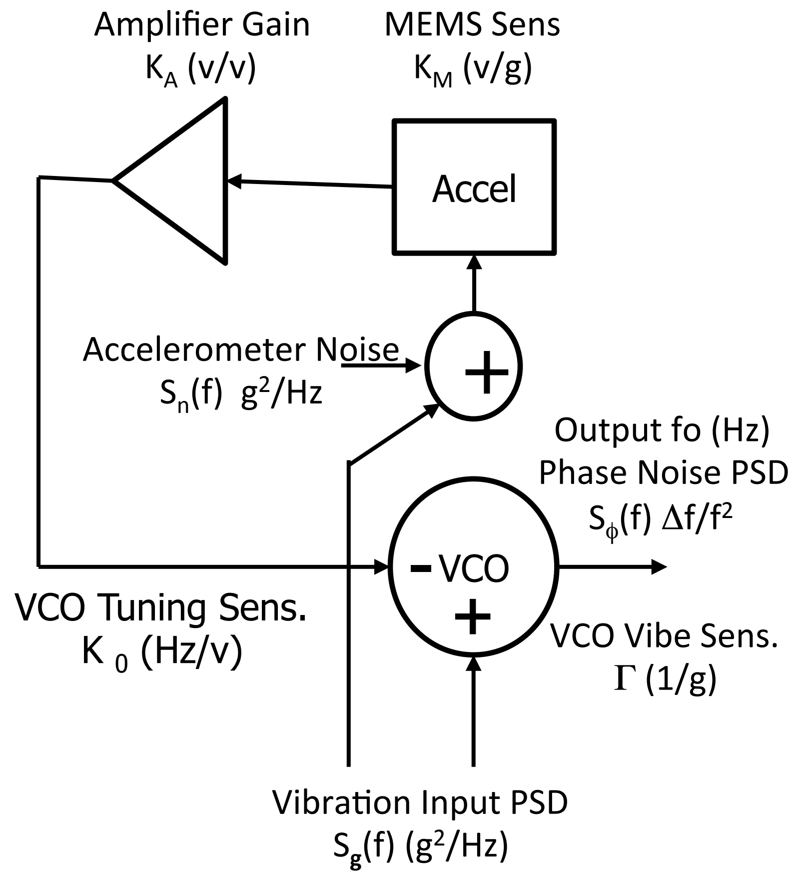


Cancellation of Vibration-Induced Frequency Change via Electrical Feedback (cont.)

- Using MEMS accelerometers, the maximum effectiveness of this technique is usually limited to several hundred Hz due to MEMS bandwidth issues.
  - Accelerometer bandwidth requirement is typically ten times the effective cancellation bandwidth.
- Ideally, this technique can be used together with mechanical vibration isolation.
  - The feedback circuitry minimizes vibration sensitivity at low frequency where the mechanical isolation system cannot.
  - The mechanical isolation system attenuates vibration at higher frequency where the feedback circuit begins to become ineffective.

Cancellation of Vibration-Induced Frequency Change via Electrical Feedback

- In addition to bandwidth issues, the static noise of the accelerometer (especially MEMS accelerometers) must be taken into consideration.
- Piezo accelerometers normally exhibit significantly lower noise and higher BW compared to MEMS devices at the expense of larger size.



In order to cancel out the VCO vibration-induced phase noise (i.e., frequency deviation):

$$\Delta f^2 = (S_g(f)(\Gamma^2)(f_0^2) - (S_g(f)(K_M^2)(K_A^2)(K_0^2) = 0$$

$$\text{or} = (\Gamma^2)(f_0^2) = K_M^2 K_A^2 K_0^2$$

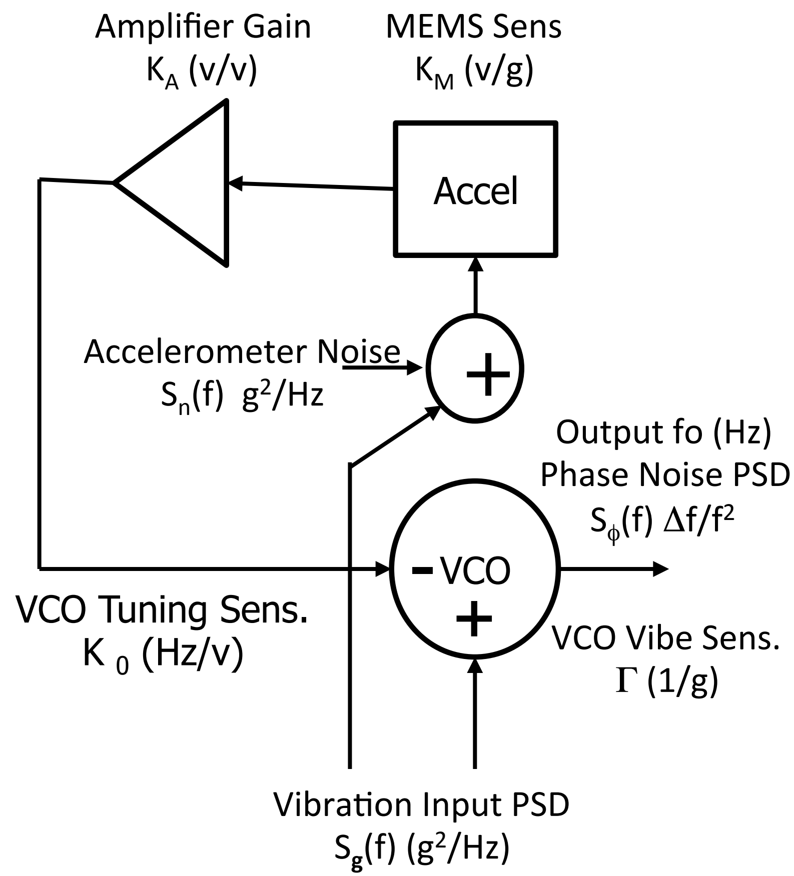
Cancellation of Vibration-Induced Frequency Change via Electrical Feedback

The accelerometer noise will cause a $\Delta f^2 = (S_n(f))(K_M{}^2)(K_A{}^2)(K_0{}^2) = (S_n(f))(\Gamma^2)(f_0{}^2)$

When the accelerometer noise is defined by a PSD (g^2/Hz), it will result in a VCO single sideband phase level of $10LOG((0.5)(\Delta f/f)^2))$ in dBc/Hz.

Thus, the accelerometer-induced, phase noise varies as:

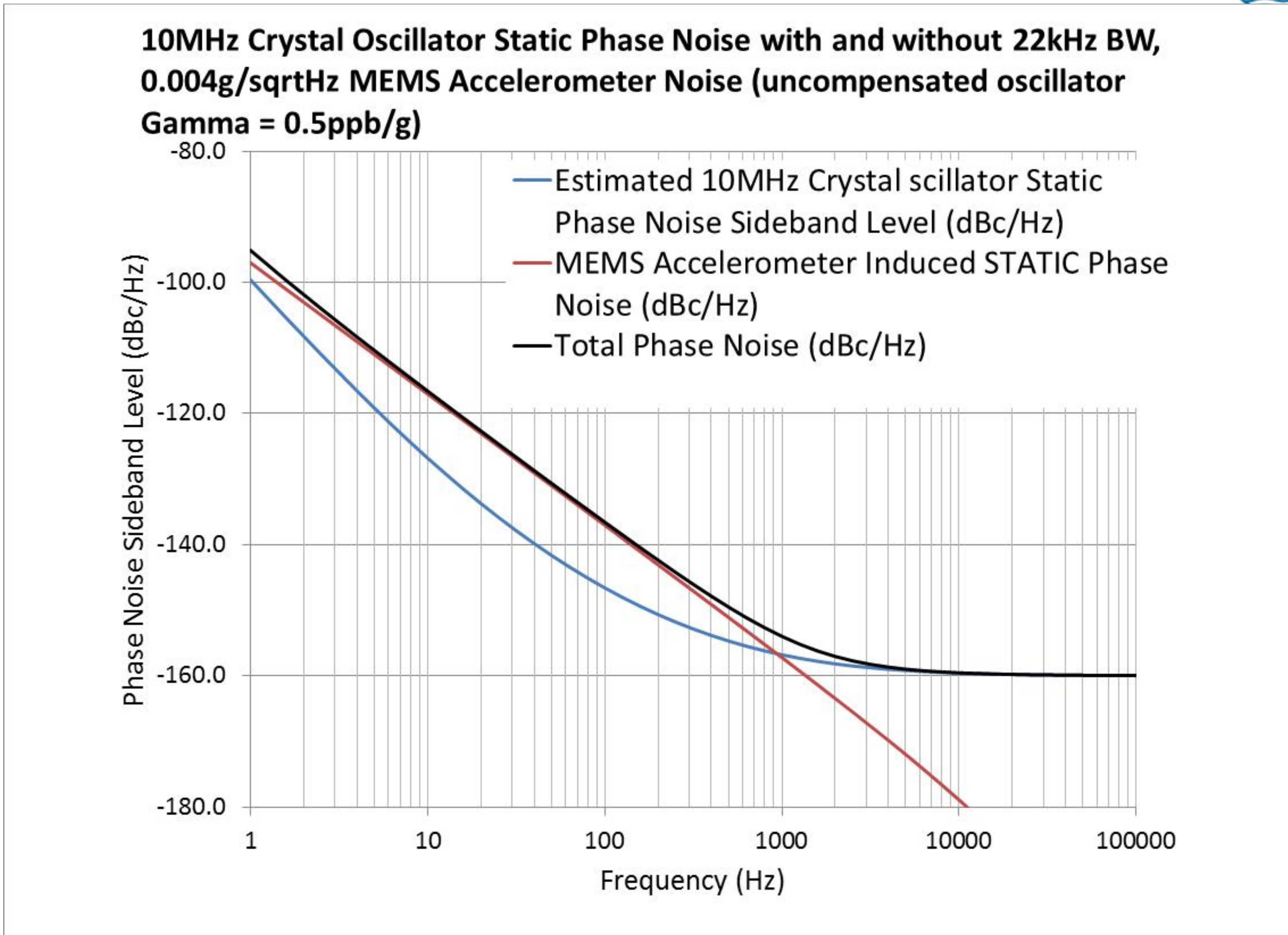
(1) the accelerometer noise
(2) the oscillator frequency
(3) the oscillator uncompensated g-sensitivity



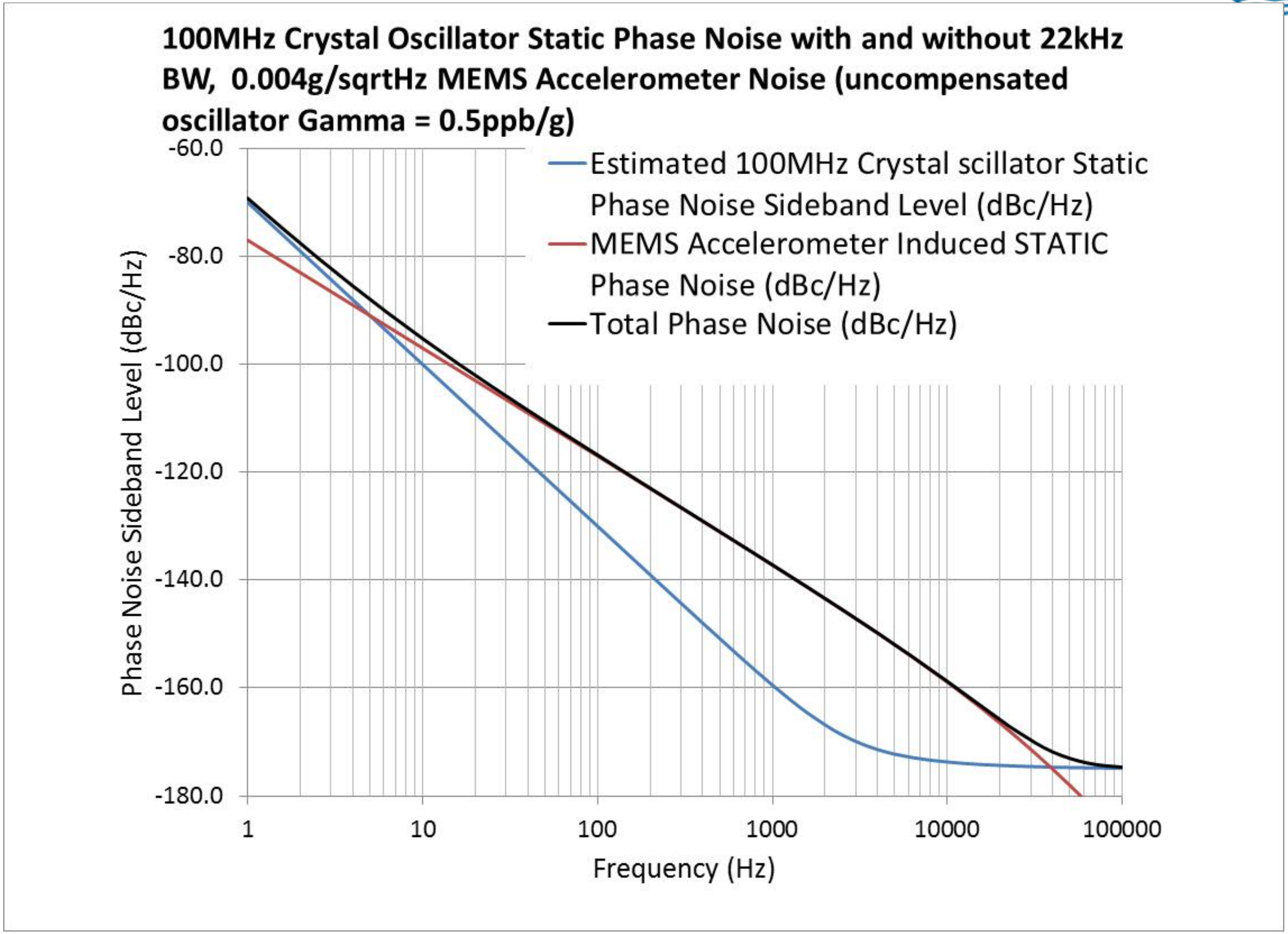
Some Accelerometer Data

Type	Noise	Noise spectral density	Bandwidth	Dynamic Range
MEMS	4000 ug/rtHz	1.6E-5g^2/Hz	22 kHz	+/- 70gs
MEMS	130 ug/rtHz	1.7E-8g^2/HZ	2.5 kHz	+/- 17gs
"Miniature" Piezo	45 ug/rtHz @100 Hz, 20 ug/rtHz @1kHz	2E-9g^2/Hz	40kHz (3dB)	+/- 1000gs

Typical Effect of Accelerometer Static Noise

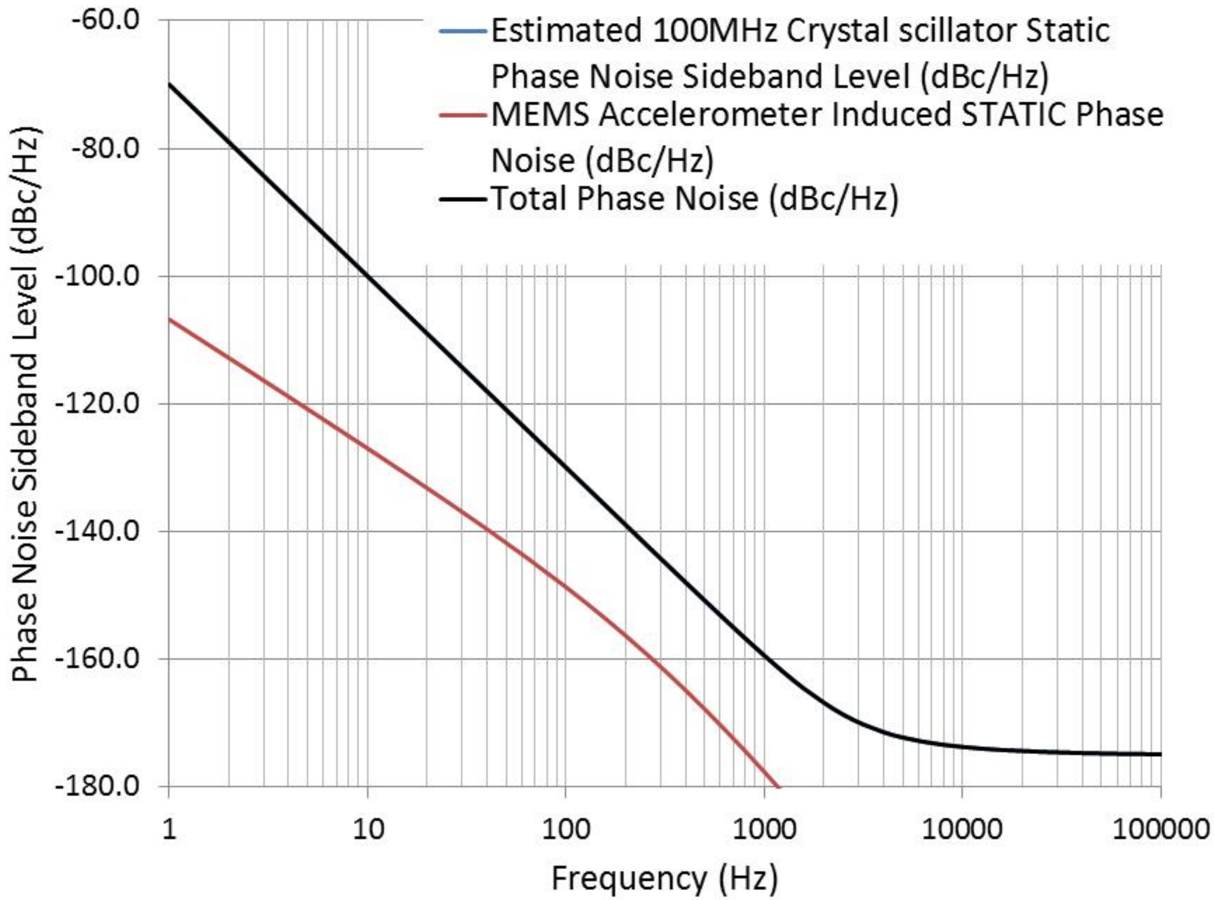


Typical Effect of Accelerometer Static Noise (cont.)



Typical Effect of Accelerometer Static Noise (cont.)

100MHz Crystal Oscillator Static Phase Noise with and without 2.5kHz BW, 0.00013g/sqrtHz MEMS Accelerometer Noise (uncompensated oscillator Gamma = 0.5ppb/g). NOTE: G-Compensation typically limited to approximately 10% of Accelerometer BW = 250Hz.



Other Vibration Level Reduction Techniques

- Careful design of structures
  - High natural frequency (stiff and light)
  - For two-stage vibration isolation, octave of separation between isolator natural frequencies
  - Damping maximized
  - Reasonably well sealed cavity to avoid direct acoustic excitation
- Applied damping materials: increase damping of existing structure
- Tuned vibration absorbers: reduce vibration at a particular frequency

Vibration-Induced Phase Noise in Non-Oscillator Components

- Oscillator vibration results in signal Frequency modulation.
- Vibration in non-oscillator components results in signal Phase modulation.
- The non-oscillator components especially sensitive to vibration include narrowband (high group delay) filters, signal path circuitry sensitive to relative motion (i.e., high impedance nodes sensitive to cover motion), and components subject to movement under vibration, such as un-staked coil windings, coaxial cables, jumper wires, etc.
- Vibration-induced, phase noise degradation in these components can exceed that due to oscillator vibration, especially at higher (greater than several hundred Hz) carrier offset frequencies.
- If/when the vibration-induced motion results in collisions, the resulting phase noise degradation usually exceeds the maximum vibration frequency.

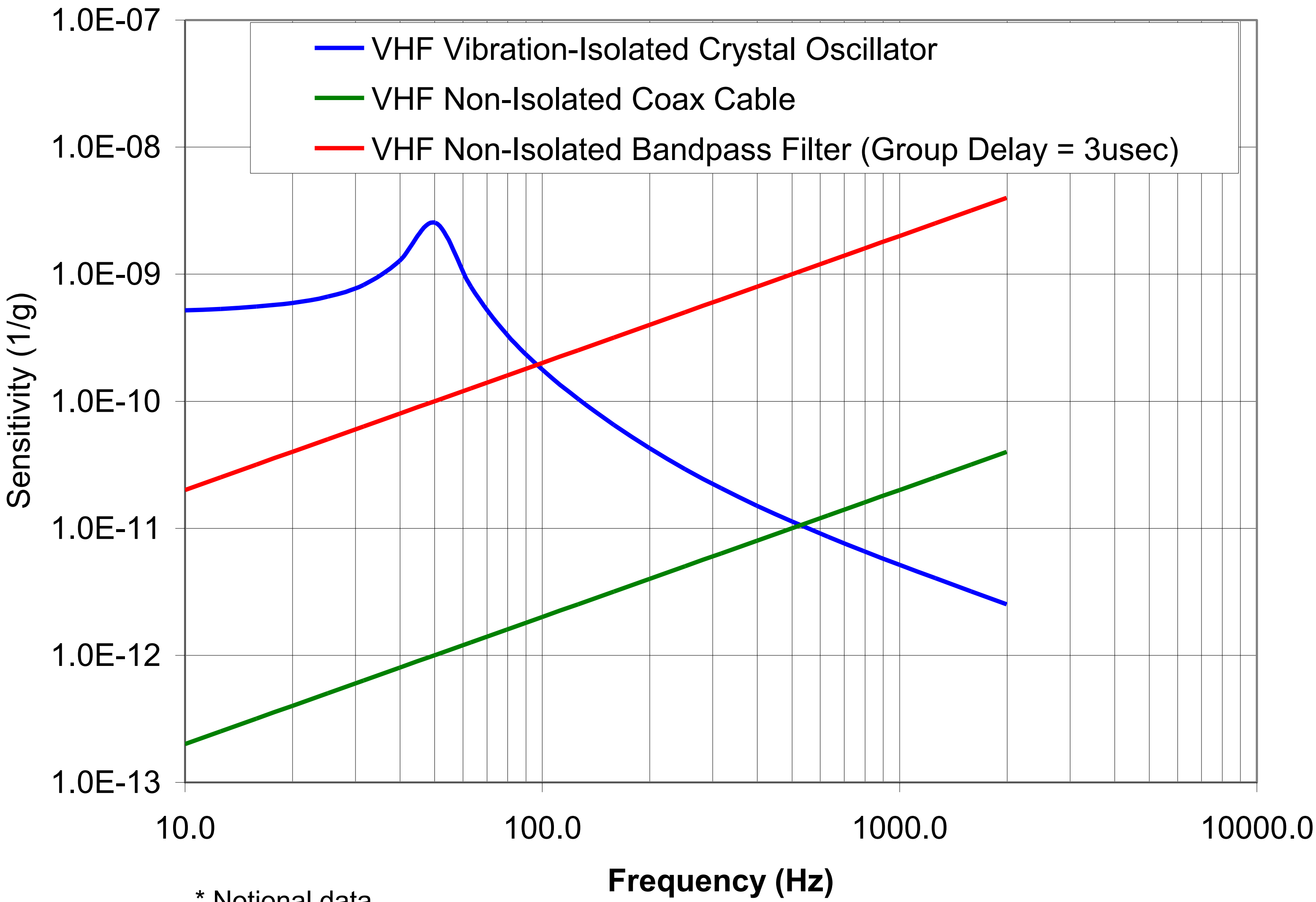
Selection and Packaging Guidelines for Non-oscillator Components

- Components which require adjustment should be avoided or cemented after tuning.
- If possible, avoid use of non-potted and non-shielded inductors.
- If possible, avoid very high circuit nodal impedances (such as those in band-pass filter and other high Q resonant circuits) sensitive to capacitance variation due to cover motion.
- Ensure hut and module covers (installed to minimize crosstalk) are sufficiently stiff and provide the greatest practical headroom so as to minimize the capacitance variation.
- If necessary, apply damping material to module covers.
- Avoid un-necessarily narrow band filters
  - the most inherently vibration sensitive component
  - often implemented with high Q resonators

Selection and Packaging Guidelines for Non-oscillator Components (cont.)

- Cable sensitivity
  - Semi-rigid cable is least sensitive to vibration but long unconstrained lengths can exhibit mechanical resonances.
  - Some flexible cables are better than others (you get what you pay for).
  - Solid or wrapped cable shields are better than braided shields.
  - Low sensitivity cables are required for connections to and from vibration isolated devices.
  - Cables should be secured along their length and prevented from scraping or intermittently hitting adjacent cables or other hardware.
  - If possible, add damping (braided-fiberglass sleeve) to cables that must be unsupported over long lengths.

Oscillator Equivalent Fractional Frequency Vibration Sensitivity*



* Notional data

Part II:
Vibration-Induced Phase Noise Testing

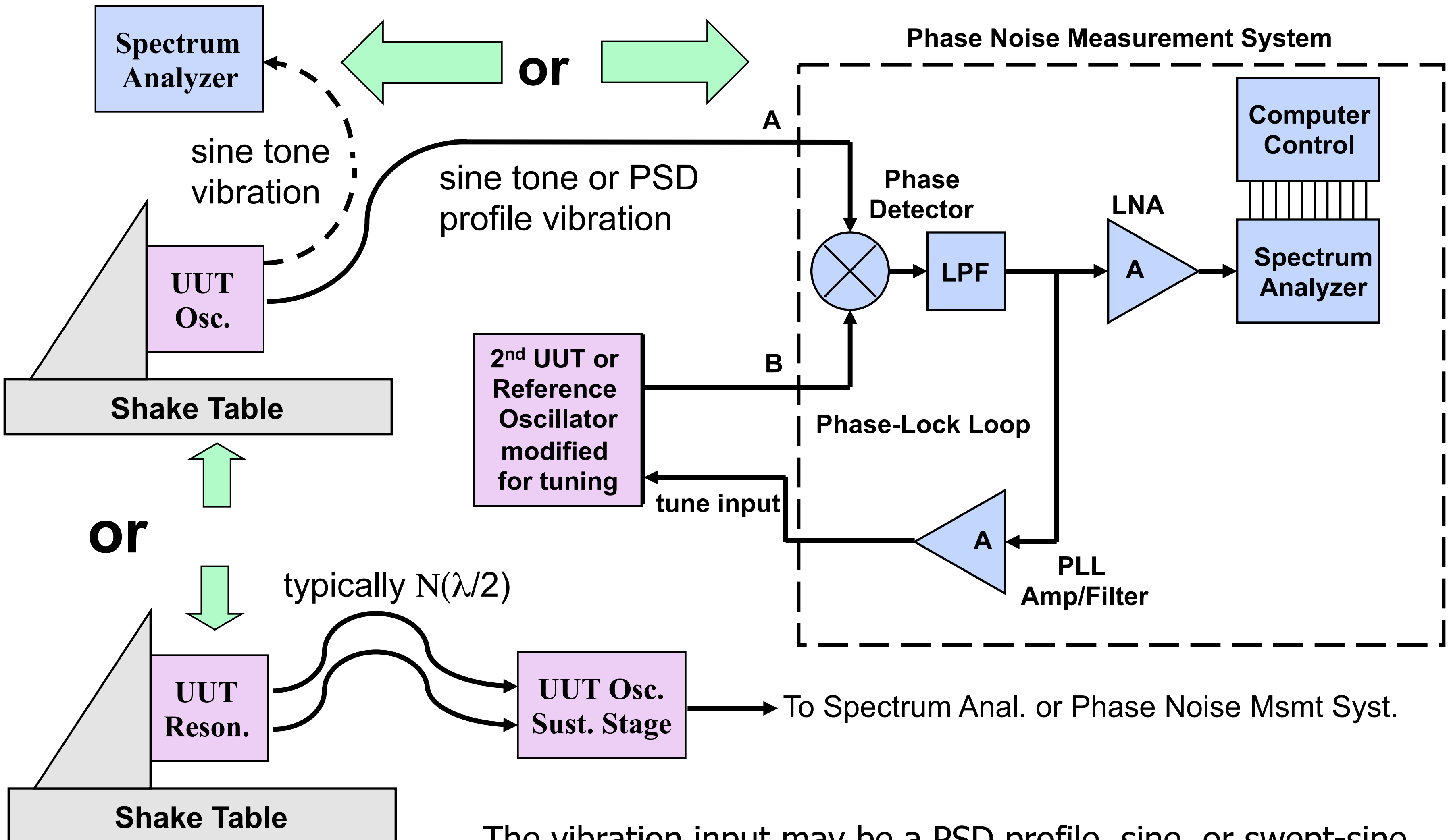
Section 1:

Phase Noise Under Vibration and Vibration Sensitivity Measurements

Measurement of Oscillator and Non-Oscillator Vibration-Induced Frequency or Phase Modulation (FM or PM)

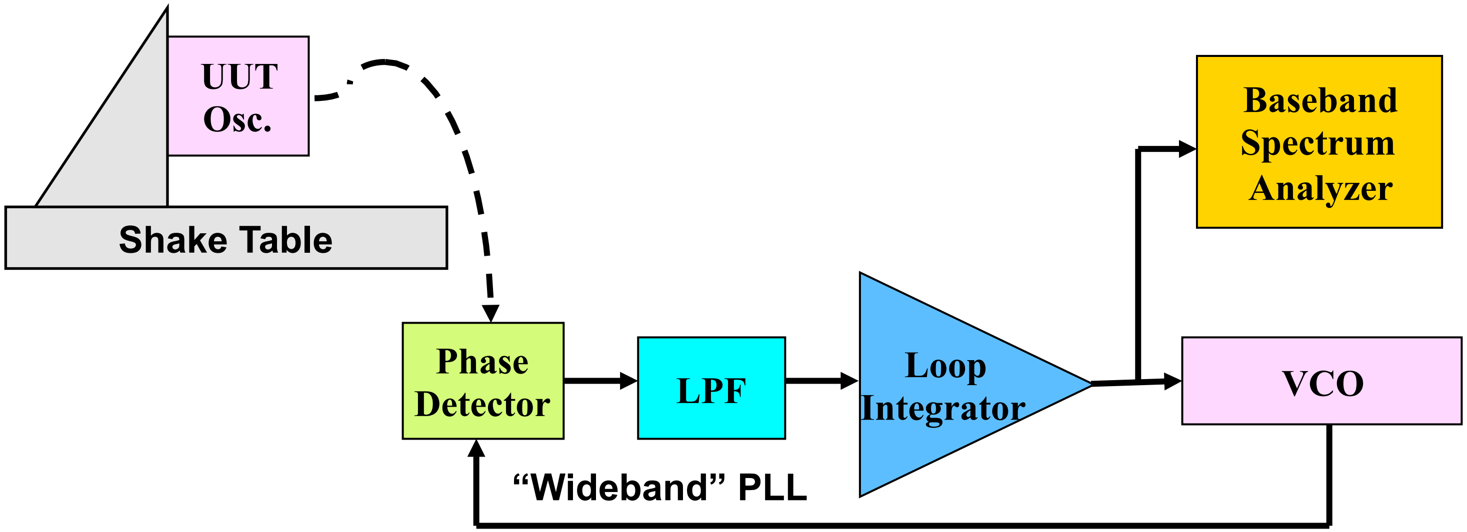
Method Number	Device Under Test (on shaker)	Measurement Method	Comments
1.	Entire oscillator	Absolute phase noise at the PLL phase detector.	Requires two, phase-locked oscillators unless cross-correlation test set is used.
2.	Entire oscillator	Measurement of phase-locked oscillator tuning voltage.	Requires a PLL bandwidth in excess of the maximum vibration frequency.
3.	Oscillator resonator(s)	Two oscillator measurement with coaxial cable connecting resonator(s) to sustaining stage. Resonator bridge measurement of vibration-induced phase modulation.	Same as method 1 or 2 above. Effects of connecting coaxial cable vibration must be evaluated and minimized. Cable length may be intentionally selected as $N(\lambda/2)$ or $N(\lambda/4)$.
4.	Non-Oscillator components	Bridge measurement of vibration-induced phase modulation. Narrowband filter sensitivity may be evaluated by using the UUT filter as an oscillator frequency control element.	Effects of connecting coaxial cable vibration must be evaluated and minimized.

In-Oscillator Measurement of Oscillator or Resonator Vibration-Induced FM



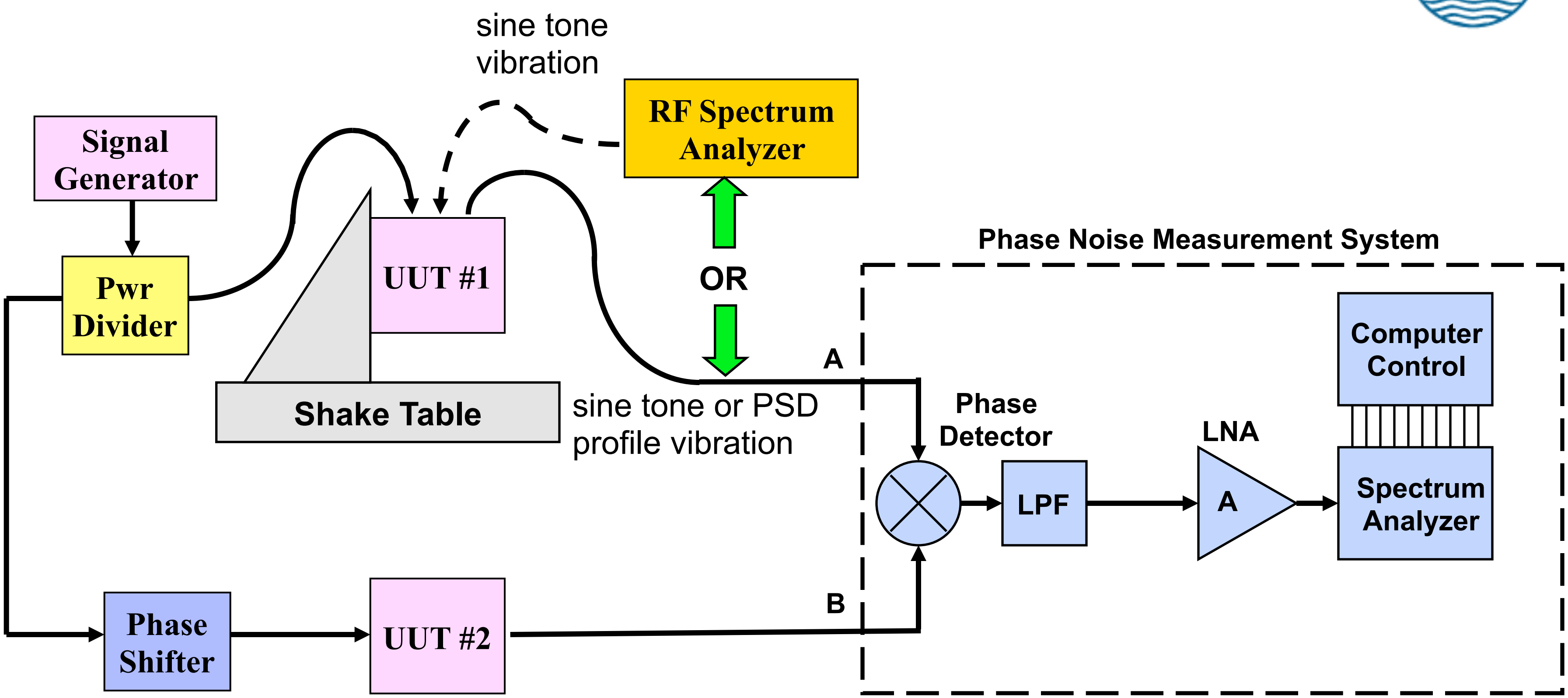
The vibration input may be a PSD profile, sine, or swept-sine.

Alternative Measurement of Oscillator or In-oscillator Resonator Vibration Sensitivity



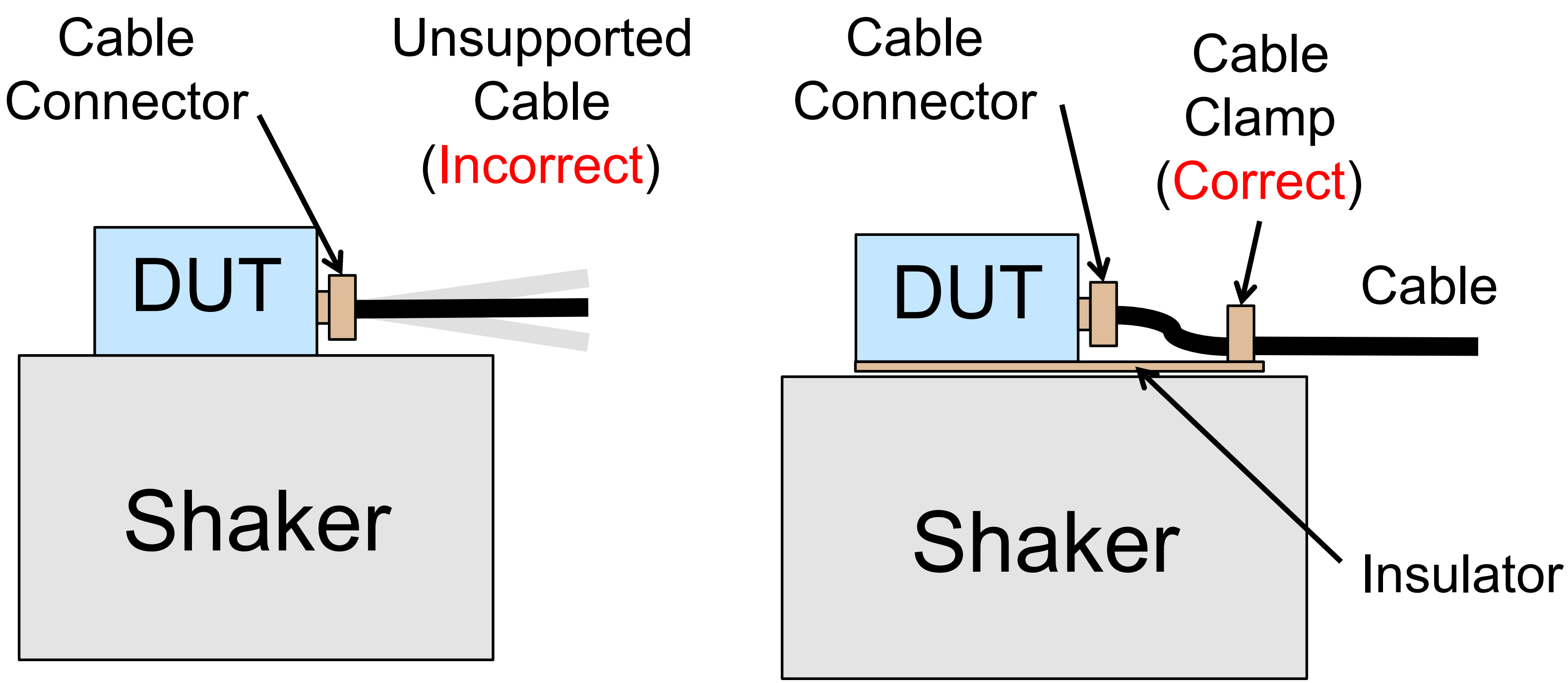
- The VCO is selected for high modulation rate capability and tuning sensitivity. Inside the PLL bandwidth, the VCO tuning voltage spectrum is a measure of the VCO plus UUT oscillator FM noise plus the vibration-induced frequency change in the UUT oscillator. The PLL acts like a frequency discriminator.
- Vibration levels need to be sufficiently high so that the vibration-induced FM sideband levels well in excess of FM noise sideband levels.
- The VCO can be a commercial, synthesized signal generator operated in the DC FM mode.

Measurement of Non-Oscillator Component Vibration-Induced PM



- Vibration induces Phase Modulation (PM) onto the carrier signal.
- If the UUT is a relatively broadband component with low group delay, a second UUT may not be required.
- The vibration input may be a a PSD profile, sine, or swept-sine.

DUT Cable Attachment and Ground Isolation

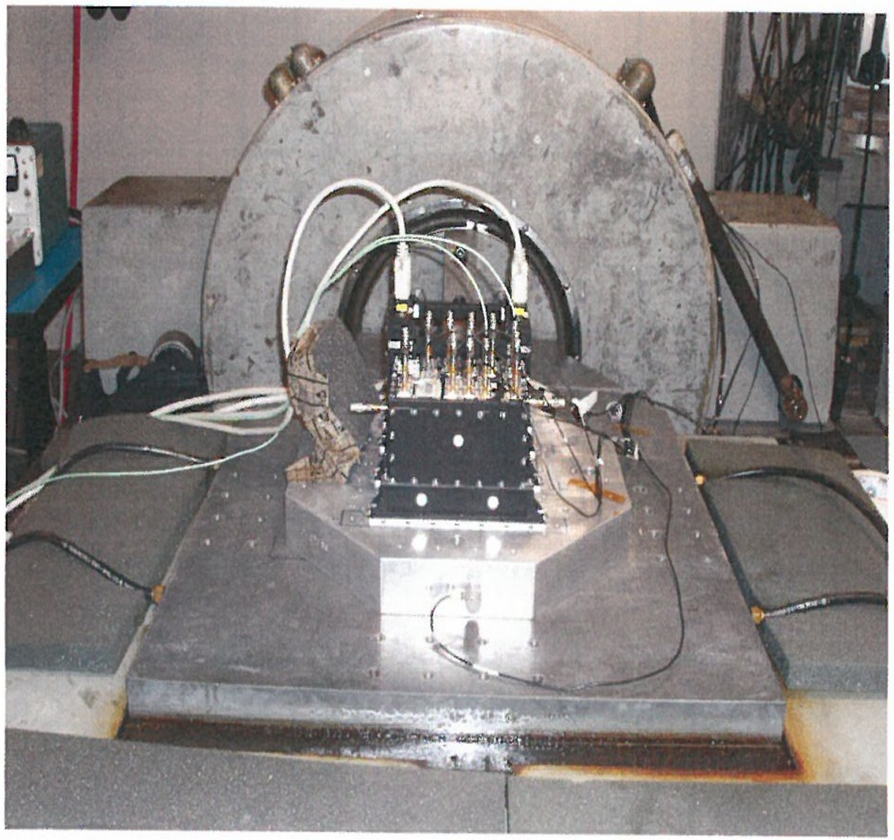


Clamp coaxial cables near DUT connector to minimize stress and motion between the cable and the cable connector.

Photograph of Phase Noise under Vibration Set-up (courtesy Frequency Electronics, Inc.)

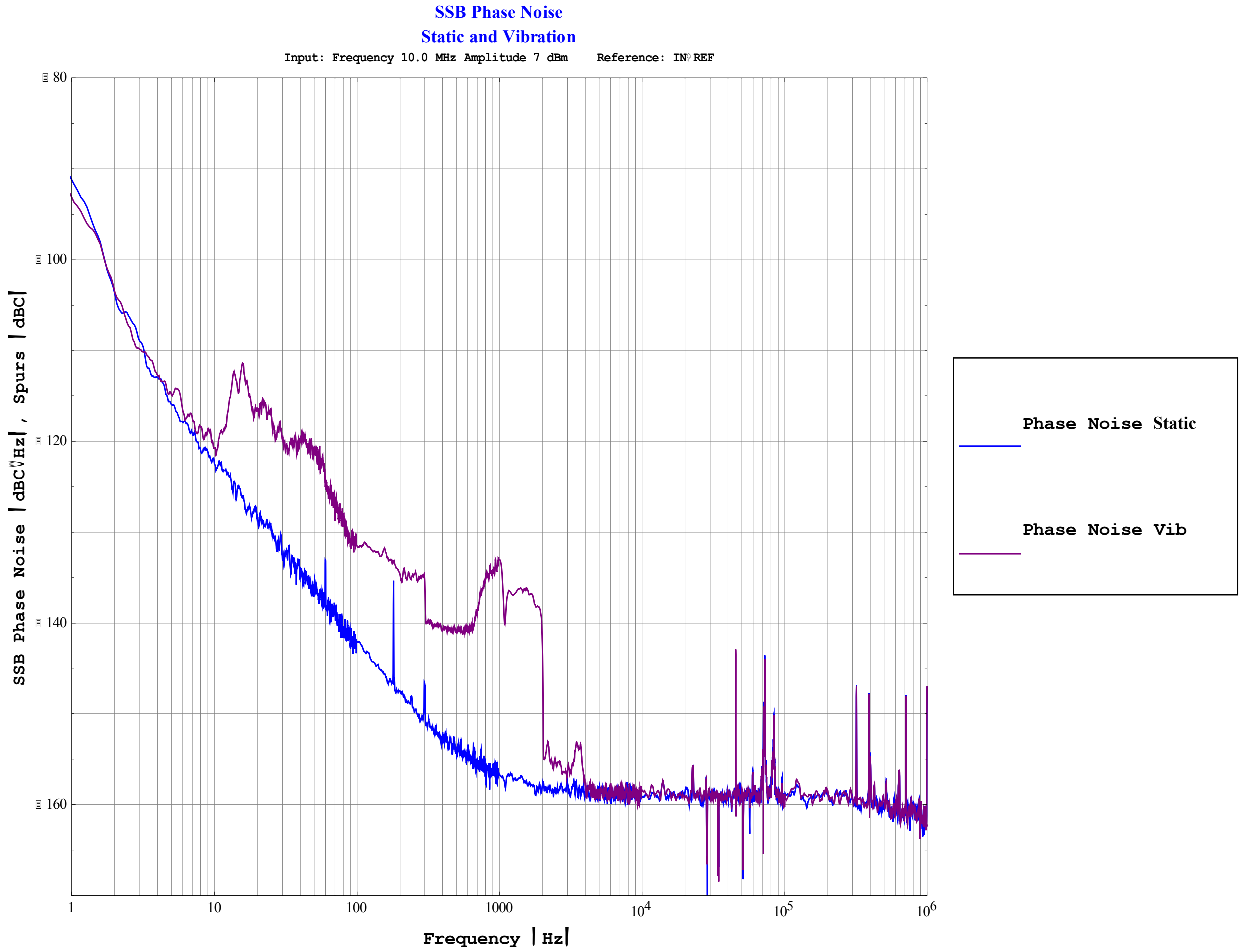
DUT subassembly mounted on vertical shake table. Note cables to/from DUT are tied down to shake table.

Photograph of Phase Noise under Vibration Set-up (courtesy Frequency Electronics, Inc.)



DUT subassembly mounted on horizontal slide plate.

Measured Results of Vibration-Induced Phase Noise PSD (courtesy Frequency Electronics, Inc.)



Tip-Over Test

- Some components (crystal oscillators) are stable enough to measure the frequency change due to gravity.
- In such cases, one can vary the acceleration from +1 g to -1 g by "tipping over" the component.

Factors Affecting the Accuracy of Oscillator and In-oscillator Resonator Vibration Measurements

- Vibration-induced FM and PM in coaxial cables, especially when the cable traversing the shaker/test equipment interface is inside the oscillator feedback loop.
- Vibration-induced oscillator signal FM attributed to resonator sensitivity, but due to relative motion in non-resonator components such as enclosure covers, cables, printed wiring board assemblies, tunable capacitors, air-wound coils, etc.
- Mechanical non-linearity. Components, surfaces scraping or hitting under vibration. This can result in vibration-induced phase noise well in excess of the maximum vibration frequency.
- Mechanical resonances in the vibration fixture or oscillator assembly.
- Insufficient reference oscillator and/or phase noise test set insensitivity to vibration and acoustic noise in the test area.
- Magnetic field, grounding and electrical pickup issues between the UUT plus Test Set equipment and the vibration equipment (shaker, shaker amplifier, blower, etc.).
- Vibration levels (induced signal FM sideband levels) that are insufficiently high, compared with circuit static FM noise.

Measurement of Multi-Function Assembly Vibration-Induced FM and PM

Method Number	Measurement Method	Comments
1.	Absolute phase noise of a signal generating assembly.	Requires use of a functionally identical assembly or a reference source providing identical (and tunable) frequency output signal(s).
2.	Residual phase noise of an assembly with identical input and output frequency signals.	Standard, phase bridge measurement.
3.	Residual phase noise of an assembly with non-identical input and output frequency signals.	Requires use of a functionally identical assembly in the second arm of the phase bridge.

Troubleshooting Techniques

Symptom	Possible Cause	Recommended Fault-Isolation Technique
High level, vibration-induced noise well in excess of maximum vibration frequency.	Mechanical non-linearity. Improperly staked cables. Lack of subassy surface flatness.	Visual inspection. Suppression of randomly occurring peaks in the test set (real time) baseband noise voltage-time waveform when pressing on suspicious subassemblies.
Unexpected noise peaks (may be plotted as discretes).	Mechanical resonances.	Suppression of noise peaks in the test set (real-time) baseband noise spectrum when pressing on suspicious subassemblies.
Higher-than expected, vibration-induced phase noise.	Vibration sensitive vendor components and cables.	Suppression of noise peaks in the test set (real-time) baseband noise spectrum when pressing on suspicious subassemblies.
Higher-than expected, vibration-induced phase noise.	UUT and/or test equipment sensitivity to test area acoustic noise.	Lift UUT off shaker (no vibration) and re-run phase noise measurement.
Higher-than expected, vibration-induced phase noise.	UUT sensitivity to test shaker magnetic field.	Increase distance between shaker head and UUT. Use mu-metal shield on shaker head.
Higher-than expected, vibration-induced phase noise.	Insufficient ground isolation between the UUT, noise measurement equipment, and vibration equipment	Mount UUT to shake table using insulating washers.

Part II:
Vibration-Induced Phase Noise Testing

Section 2:

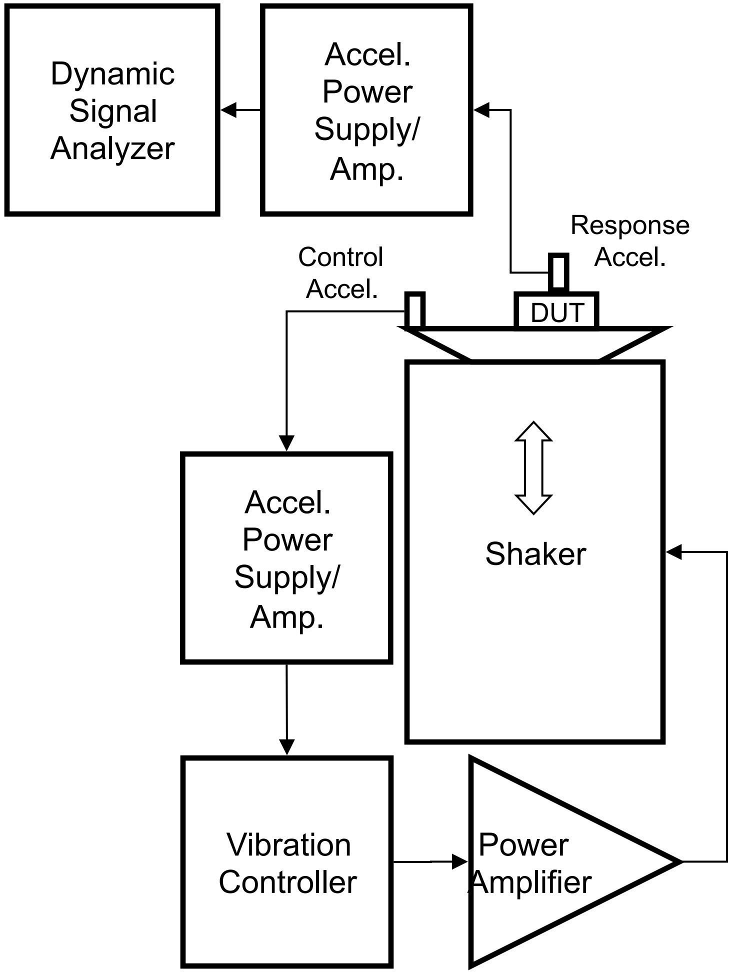
Vibration Testing

Slides 61-74 prepared by Joseph Donovan*

*"Vibration-Induced Phase Noise in Signal Generation Hardware" presented at the 2009 RFTF/IFCS Conference in Besancon, France.

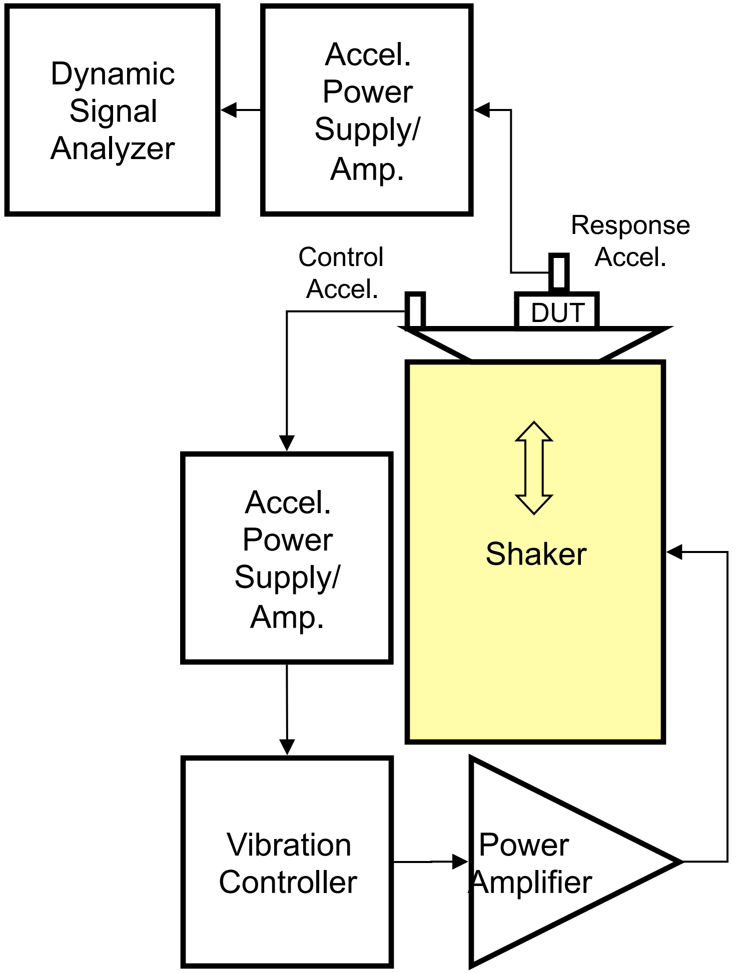
Typical Vibration Test Setup

- Types of vibration supported
  - Discrete
    - Sine(s) dwell
    - Swept/stepped sine
  - Broadband
    - White noise random
    - Colored/shaped spectra
  - Combinations of discrete and broadband
  - Transient (shock)
    - Not common for phase noise testing
- Constant acceleration not supported
  - Aside from gravity



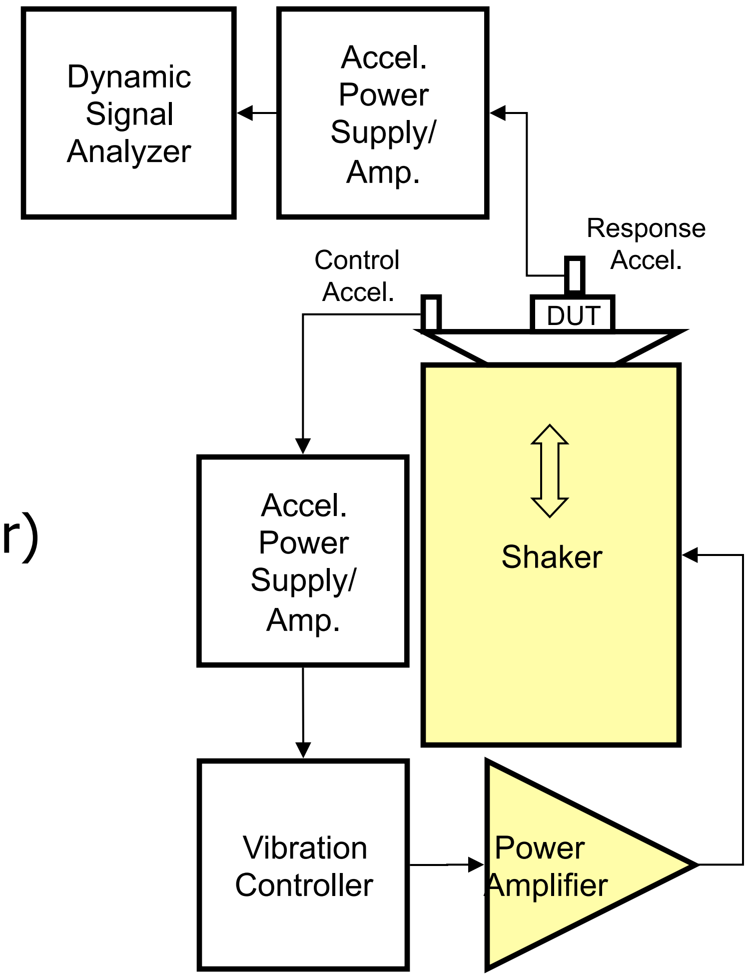
Shakers and Axes

- Shaker
  - Moving coil in a magnetic field (permanent or electromagnetic)
  - Essentially converts electrical current into force
- Axes
  - Single axis
  - 3 axis sequential
  - Multi-axis simultaneous



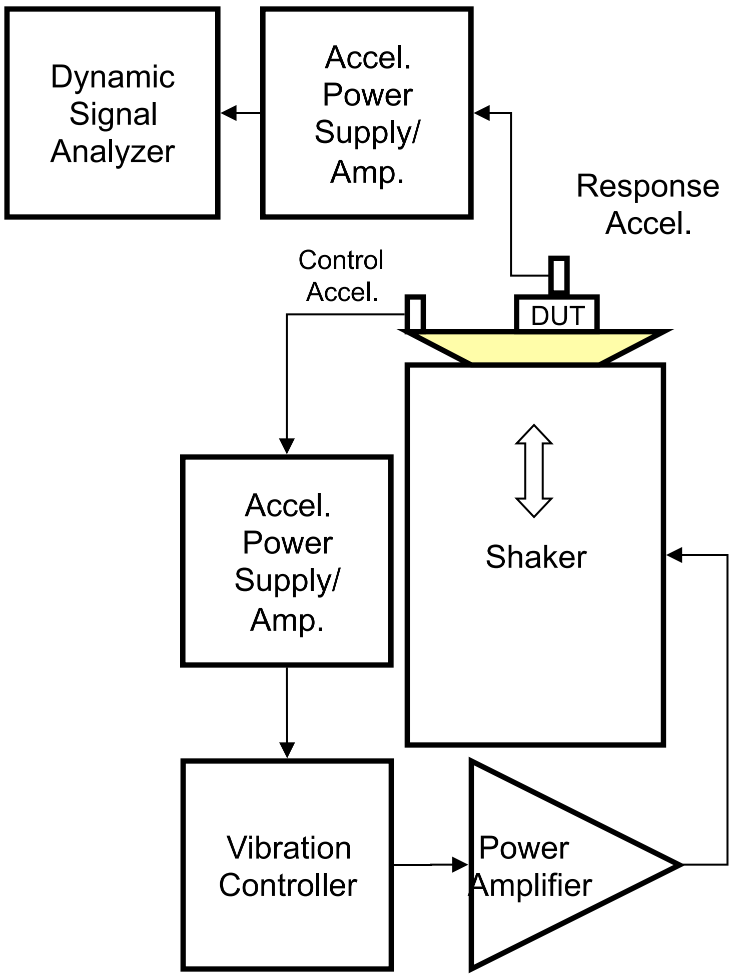
Vibration Level Limitations

- Shaker limits
  - Dynamic stroke
  - Force
- Power amplifier limits
  - Velocity
  - Minimum controllable level (noise floor)
- Typical tolerances
  - Alarm at +/- 1.5 dB
  - Abort at +/- 3 dB



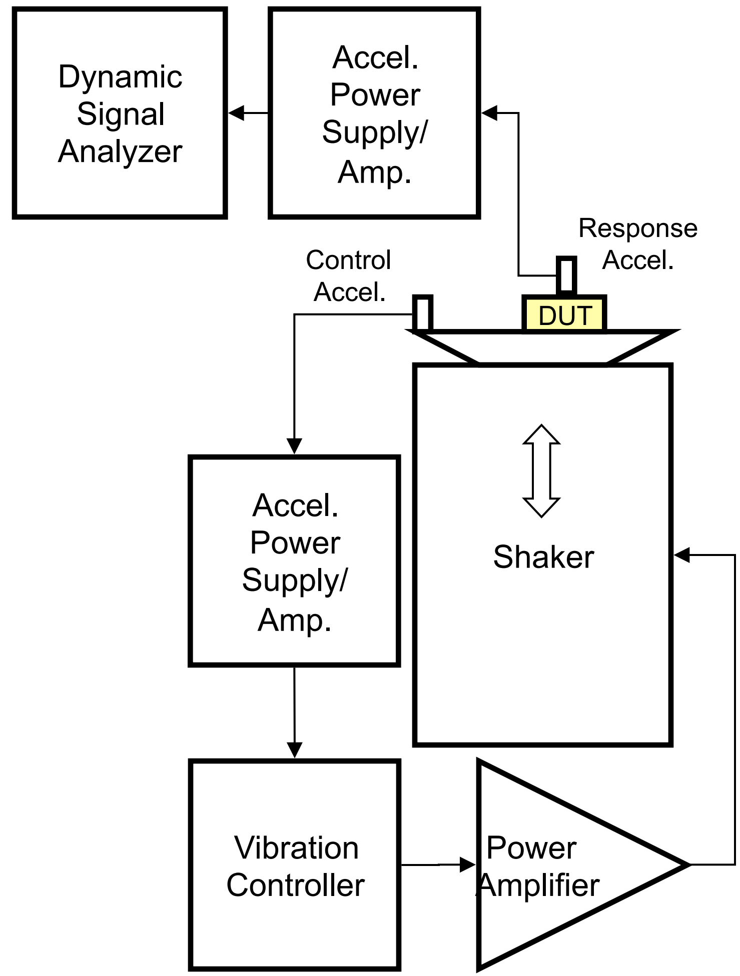
Fixtures

- Goals
  - Provide necessary attachment points for DUT
  - Provide necessary attachment points for shaker
  - High stiffness and low mass
- Slide-plate
  - Permits horizontal excitation without a radial gravity load on the shaker
  - Permits longer distance between DUT and shaker (lower magnetic field)



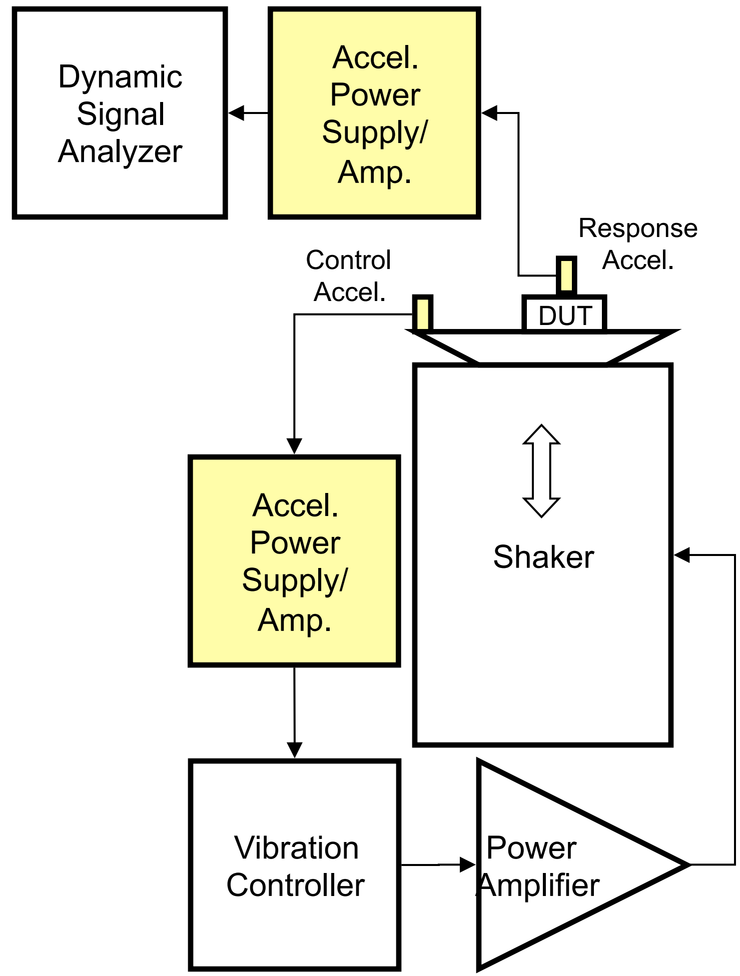
Configuration of the DUT

- Uniform
  - All parts of DUT are in motion
  - Only test-set cables undergo relative motion
- Differential
  - A portion of the DUT is in motion



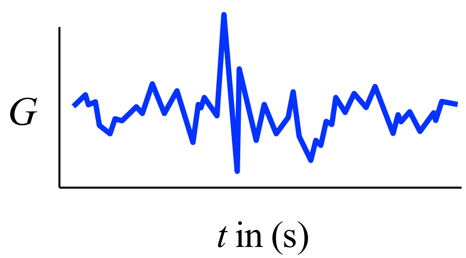
Sensors

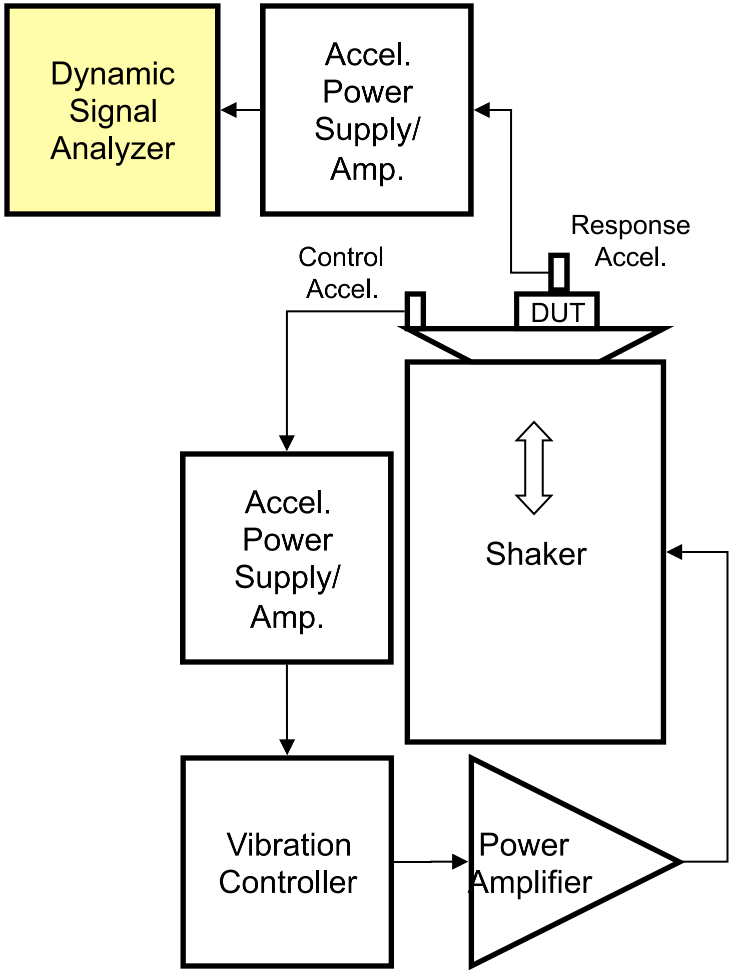
- Piezoelectric accelerometers
  - Cannot measure very low or very high frequencies
- Other accelerometers
  - Can measure very low frequencies
- Laser Doppler Velocimeter
  - non-contact velocity measurement
  - single-point or scanning
- Displacement sensors
  - Contacting
    - LVDT
    - Potentiometer
  - Non-contacting
    - Laser triangulation
    - Eddy current and capacitive
- Most sensors require some sort of amplification and/or signal conditioning



Time Domain Analysis

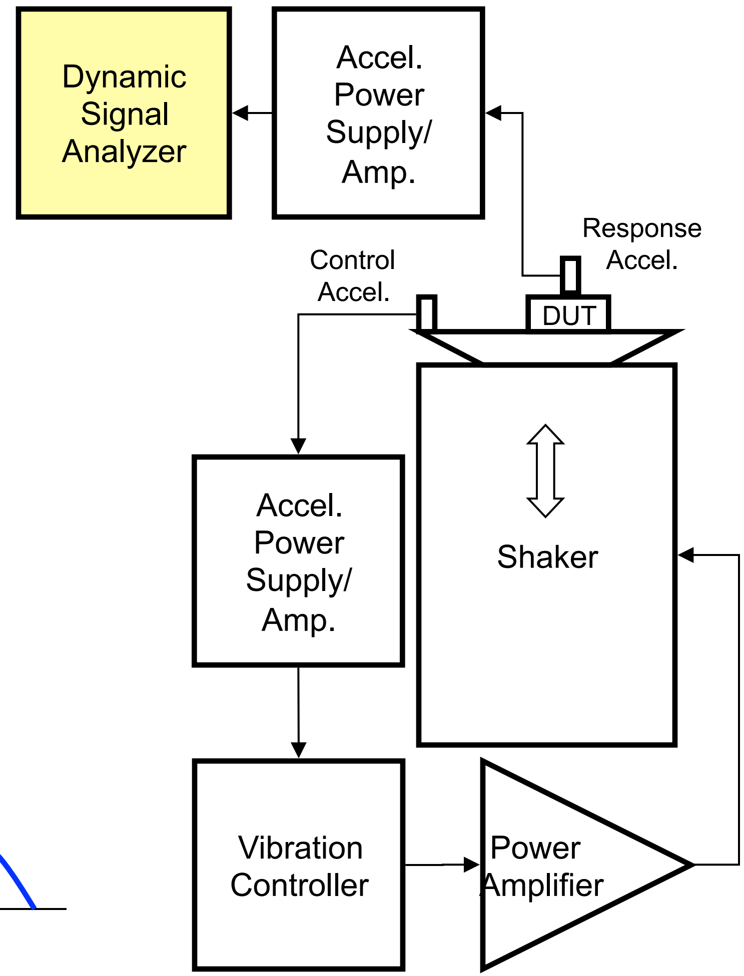
- Can be compared to "real time" phase noise measurements
- Randomly occurring impulse-like peaks may indicate intermittent noise

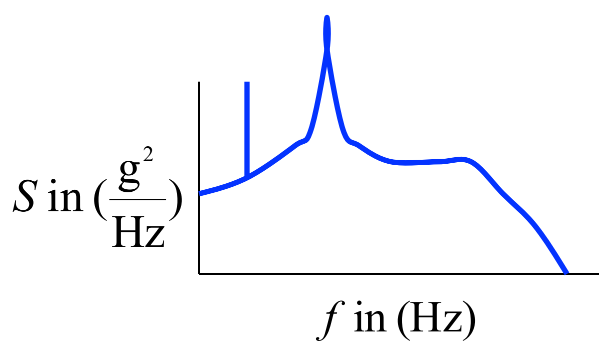




Frequency Domain Analysis

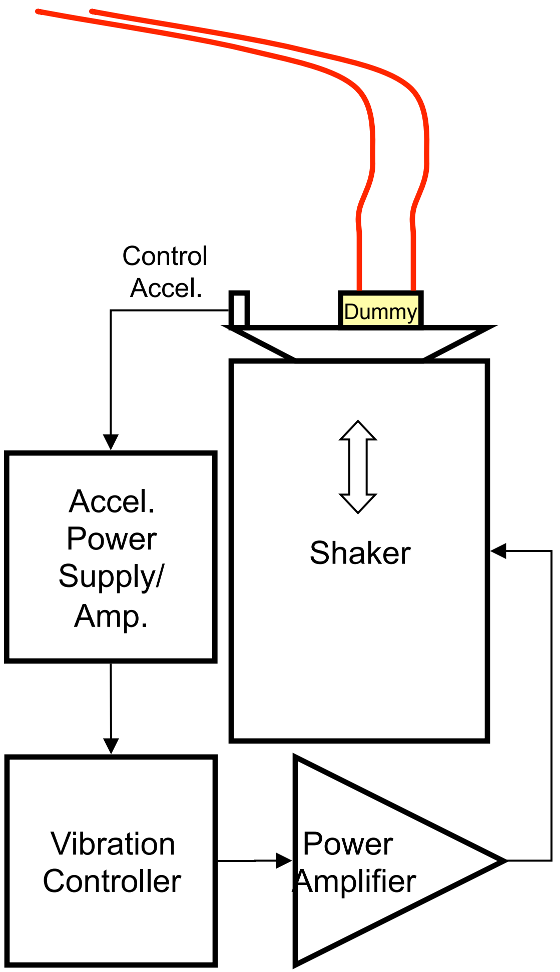
- Best for comparison to phase noise spectra
- Obtained via Fourier transform
- Several PSDs averaged to remove uncorrelated noise
- Gives clear indication of
  - Discretes
  - Resonances
  - Overall level





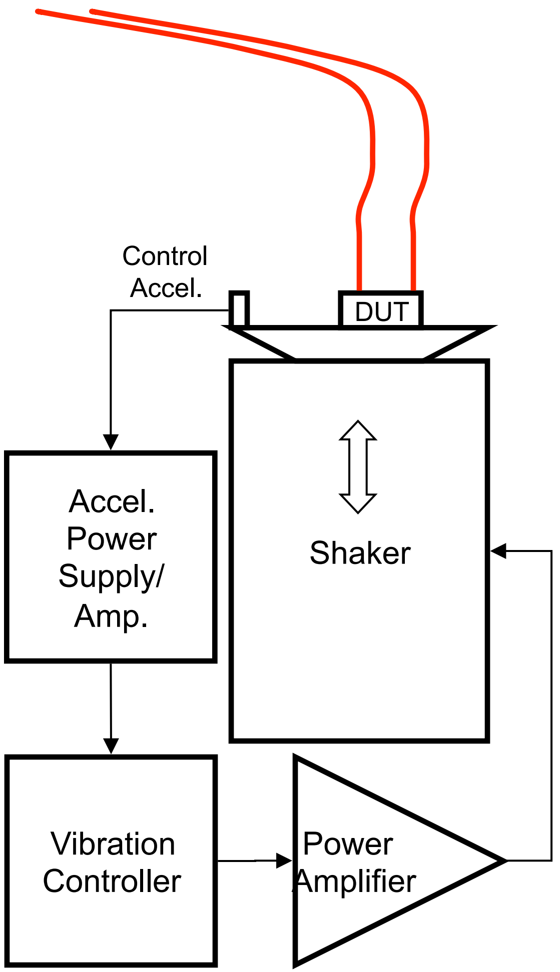
Baseline Calibration

- Baseline Calibration without the DUT
  - Reduce all sources of vibration-induced phase noise except DUT sensitivity
  - Test includes everything in test set but DUT
  - Usually requires “dummy” DUT with a simple “through path”
- <u>Not</u> the same as a static measurement
  - Vibration is applied
- Once you have established a good baseline
  - Leave the test-set alone
  - Check the baseline <u>daily</u>
- An alternative baseline calibration may use the same, specific DUT with known (measured) PM noise under vibration.



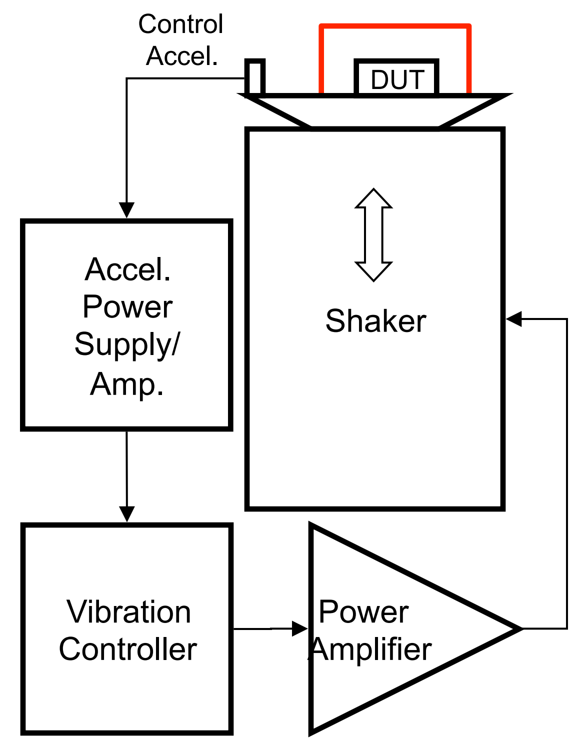
Test-Set Cables

- Cable type
  - All cables are sensitive – some types more than others
  - Semi-rigid is usually the best choice
  - Some manufacturers consistently produce flexible cables with low sensitivity
- Routing
  - Prevent vibration from traveling along the cables to test-set
  - Clamp cables to fixture
  - Provide a generous service loop
  - Clamp cables to a massive stationary object



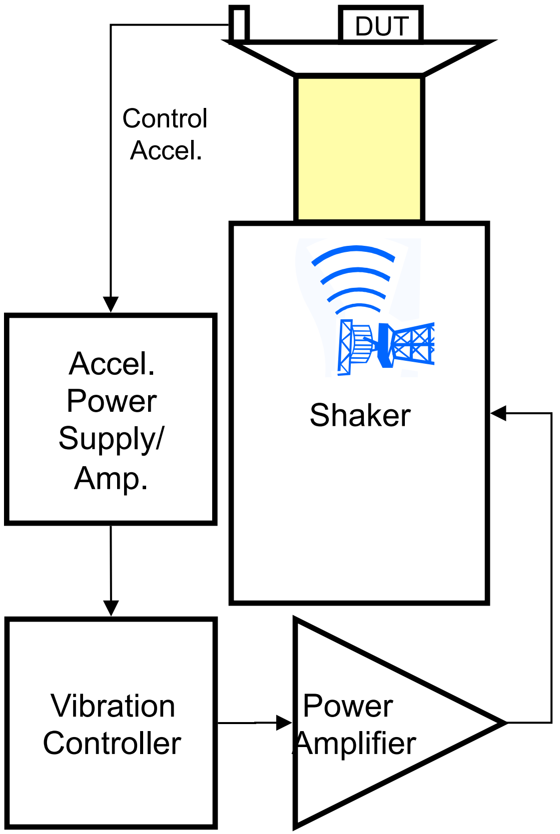
Ambient Acoustics

- Acoustic noise generated by shaker
  - Can be quantified by disconnecting the DUT from shaker but raising it just off of the shake table
  - Separate the test-set from shaker
- Acoustic noise generated by blowers, etc.
  - Often produce spurious noise
  - Enclose blowers and run air through long hoses
  - May be able to turn blowers off for a short time to determine DUT sensitivity
- Enclosing DUT is an option



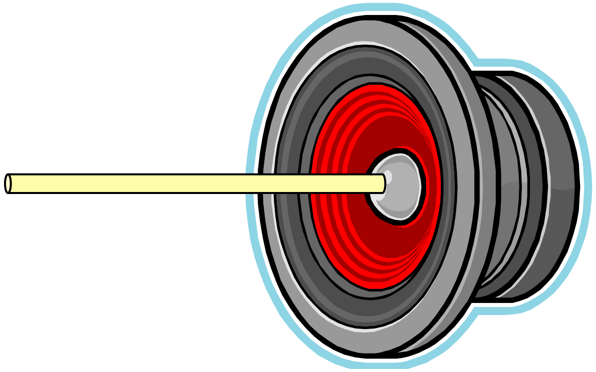
EMI

- Shakers emit two kinds of magnetic fields
  - The static "field coil" or permanent magnet
    - Shielding of the shaker and/or DUT may be required for some oscillators
  - The dynamic "voice coil"
    - This effect can be quantified by disconnecting DUT from shaker but keeping it close
  - Increasing the distance from shaker and magnetic shielding are options
- EM radiation is emitted from power amplifiers, overhead lighting, etc.
  - Place test-set in a screen room
- Ground Noise
  - Shaker is grounded to other sources of noise
  - Insulate the DUT ground from the shaker/ fixtureground
  - Place test-set on a separate AC circuit from vibration test equipment

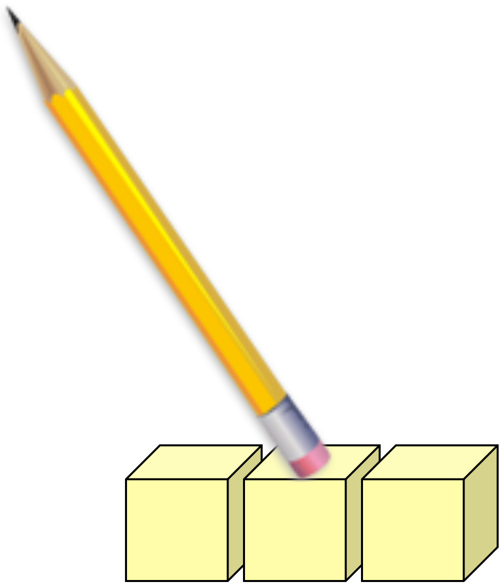


Methods of Locating Sensitive Components

- Selective excitation
  - Stinger on shaker or loudspeaker
  - Engraving tool



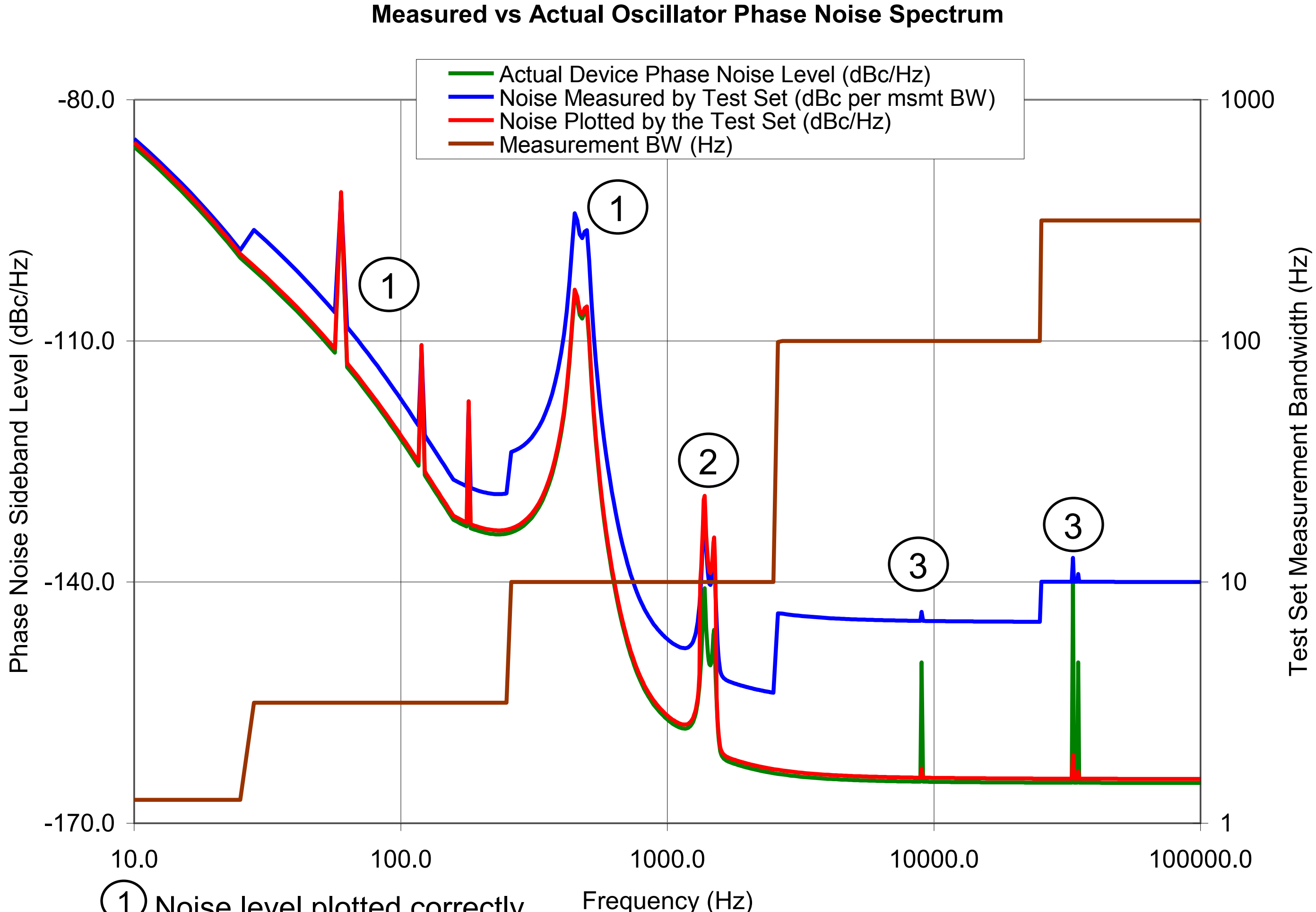
- Selective immobilization
  - Fingertip or pencil eraser



Measurement Bandwidth Issues

- Definition Bandwidth
  - Standard measures of noise in the frequency domain (i.e., $\mathcal{L}(f)$, $S_\phi(f)$, $S_y(f)$ are defined on a per Hz bandwidth basis.
- Measurement Bandwidth
  - Standard phase noise test equipment results are plotted in a 1Hz bandwidth, but the actual, measurement bandwidths are normally greater than 1Hz.
  - For white noise, the noise level (power spectral density, sideband level, etc.) increases as 10LOG(bandwidth).
- Measurement Errors
  - When measurement bandwidths are larger than plotted (1Hz) bandwidths, discrete spurious signals may go undetected.
  - Additionally, narrow bandwidth noise peaks may be erroneously interpreted as discrete (zero bandwidth) signals whose amplitude is not (but should be) adjusted on a measurement bandwidth basis.

Vibration-Induced Phase Noise Test Set Measurement Errors



1 Noise level plotted correctly.

2 Noise level plotted incorrectly. Due to the rapid noise level change, this noise peak was interpreted as a “zero BW discrete signal, and no bandwidth-related, level correction was made.

3 Noise level plotted incorrectly. Due to the large measurement bandwidth, the discrete spurious sideband was masked by the white noise level.

Summary

- New technologies and techniques are being developed that result in signal generation circuitry exhibiting extremely low, static noise levels as well as improved vibration sensitivity.
- In spite of these improvements, the spectral degrading effects of vibration remain a difficult problem limiting system performance, especially for low noise signal generation hardware housed in moving platforms.
- Automated phase noise measurement equipment dynamic range has also improved, but measurement results can be inaccurately characterized by issues such as measurement bandwidth and software used to discriminate between narrow noise peaks and discrete spurious signals.

Questions?