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Vibration-Induced Phase Noise in Signal Generation Hardware

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Tutorial Objectives – That attendees be able to:

- Identify sources of vibration-induced phase noise and discrete spurious signals
- Translate between different methods of specifying vibration sensitivity and allowable levels of vibration
- Sub-allocate phase noise and vibration sensitivity requirements to subassemblies
- Evaluate 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
- Be familiar with measurement methods and troubleshooting techniques

Agenda

- Part I: Vibration-Induced Phase Noise Analysis
  - Section 1: Review of Static Phase Noise Metrology and Performance
  - Section 2: Vibration-Induced Phase Noise
  - Section 3: Typical Vibration Sensitivity Values and Improvement Techniques
- Part II: Vibration-Induced Phase Noise Testing
  - Section 1: Phase Noise Measurement
  - Section 2: Vibration Testing

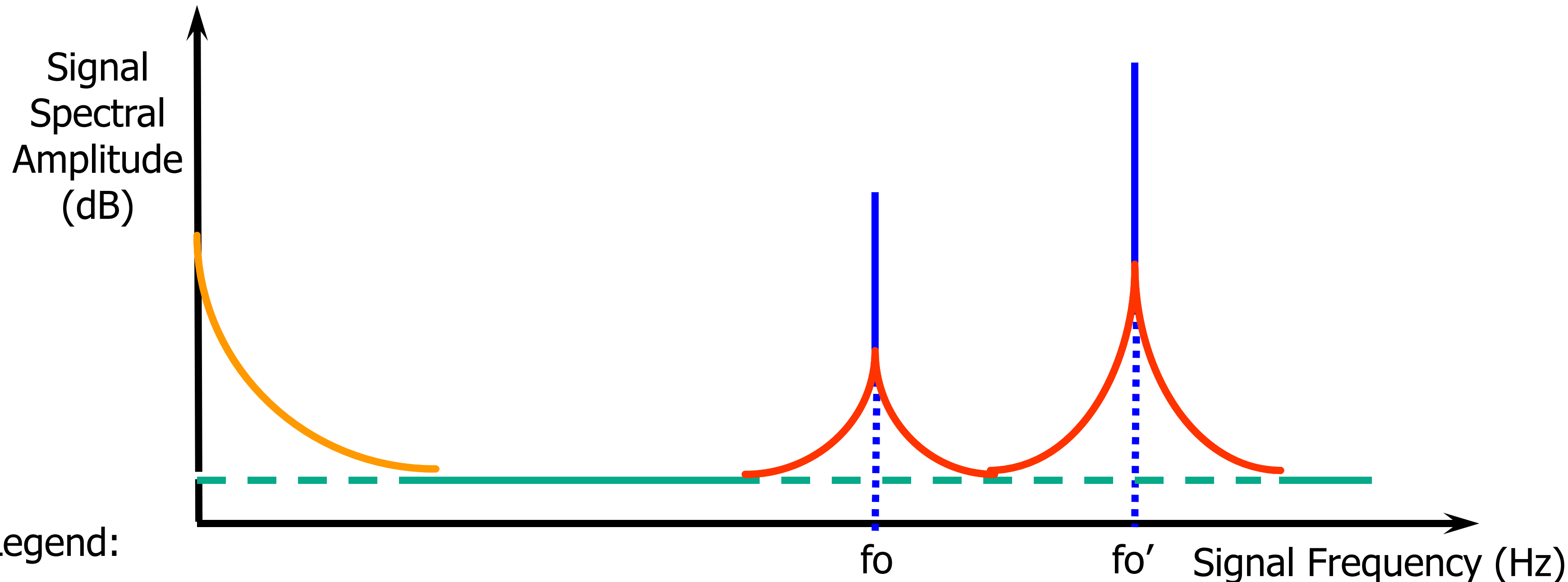
Section 1:

Review of Static Phase Noise Metrology and Performance

Origins of 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 caused by emission of electrons, photons, or passage of carriers across potential barriers
    - thermal noise caused by carrier collisions with the lattice
    - partition noise caused by the splitting of carrier or photon current
    - generation-recombination noise caused by the generation and recombination of hole-electron pairs
    - flicker noise or 1/f noise, characterized by a 1/f power spectrum
  - 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.

Multiplicative vs. Additive Phase Noise



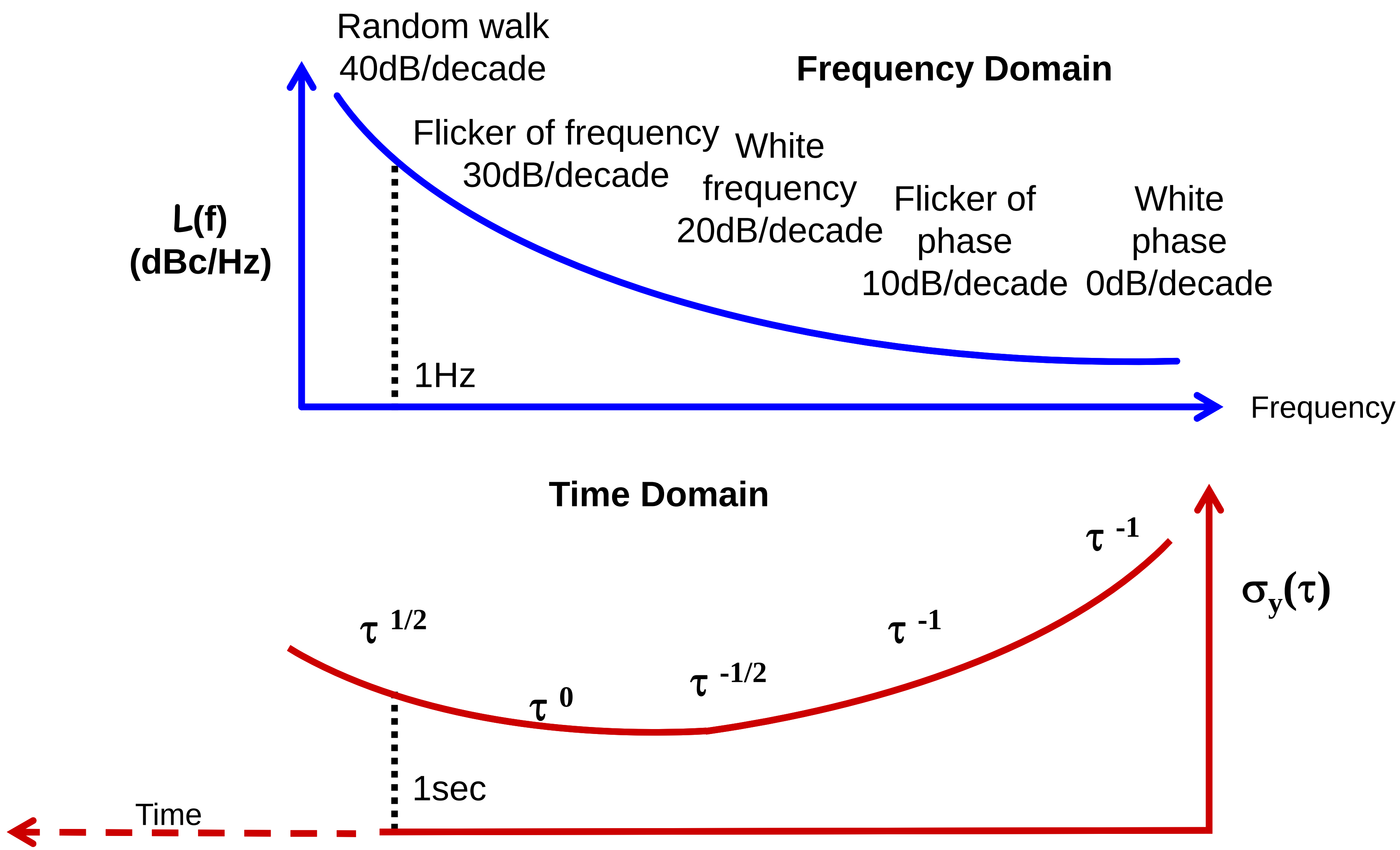
Legend:

- Carrier signal(s).
- Additive Noise whose level is independent of carrier signal level.
  Thermal (KTB) noise = -174dBm/Hz (1/2 PM, ½ AM).
- Baseband noise (usually flicker in nature).
- Multiplicative Noise whose level is not independent of carrier signal level.
  This noise may be up-converted from baseband via device non-linearity,
  or additionally due to carrier modulation due to DC supply noise or noise voltage
  modulation of semiconductor junction capacitance….or vibration-induced carrier
  signal modulation.

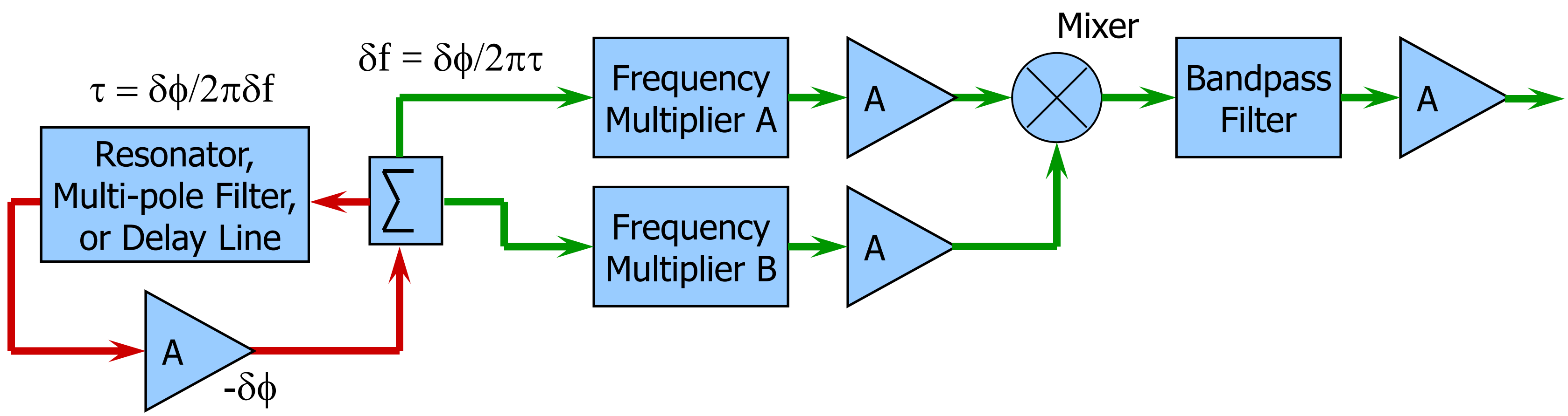
Frequency/Phase Stability Specified in the Frequency or Time Domain

- 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).
  - $S_y(f) = (f/\nu_o)^2 S_\phi(f)$, ν_o = carrier frequency.
  - $\mathcal{L}(f) = S_\phi(f)/2$.
  - For small modulation indices, $\mathcal{L}(f)$, expressed in dB = $10LOG(S_\phi(f)/2)$ = 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.

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Section 2:

Vibration-Induced Phase Noise

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. Discrete Vibration

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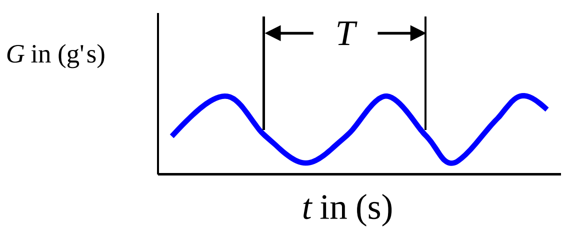
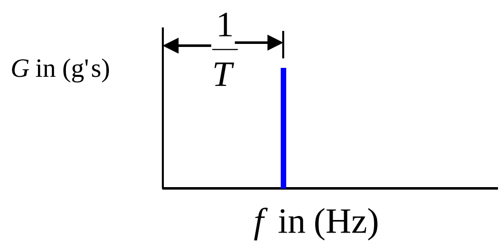
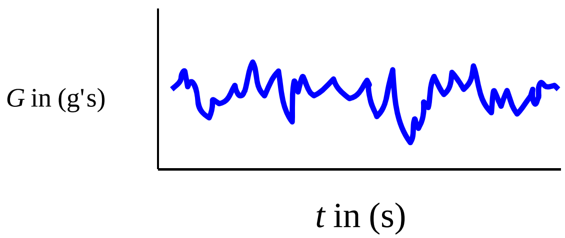
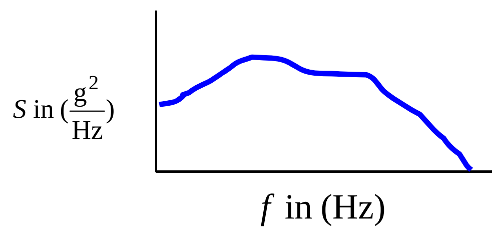
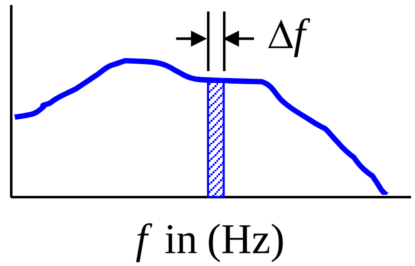
	Time Domain	Frequency Domain	Peak Amplitude
Discrete			$\sqrt{2}$•RMS
Broadband			≈3•RMS

Power Spectral Density

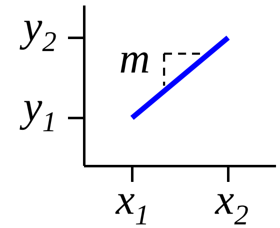
- Amplitude of broadband vibration at a particular frequency is meaningless
- Power of the vibration in an arbitrary band of frequencies (bandwidth) is meaningful

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



- Use units that are proportional to power (amplitude squared)
- Divide power by bandwidth to form density in order to make specification of bandwidth unnecessary
- Analogous to power spectral density of phase fluctuations (rad^2/Hz)

Logarithmic Interpolation



- Sloping lines on log-log PSD plots are often 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
- If the endpoints are given and an intermediate point is desired then first calculate the slope

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

- 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

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<u>Components</u>

- Transmission lines and connectors
- Air-core inductors
- Filters
- Substrates
- Oscillator loop
- Oscillator/resonator

<u>Mechanisms</u>

- Mechanical strain
- Intermittent contact
- Electromagnetic field strength variation

Fractional Frequency Sensitivity

- Most work in the field of vibration-induced phase noise has been done for oscillators – the most sensitive component
- *Fractional frequency sensitivity* is the appropriate measure of sensitivity and is obtained by measuring the change in frequency under vibration

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

  - where Δf_o is the carrier frequency error in Hz
- Fractional frequency sensitivity tends to be constant over vibration frequency except at an internal resonance
- The fractional frequency sensitivity is a function of vibration frequency, direction, and temperature

Phase Error

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- In an oscillator the *phase error* is related to the frequency error by

$$\Delta\phi = \frac{\Delta f_0}{f}$$

- Power spectral density of phase fluctuation is another way to quantify phase error

$$S_\phi = \frac{\Delta\phi_{RMS}^2}{\Delta f}$$

  – where Δf is the definition bandwidth in Hz

Phase Sensitivity

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

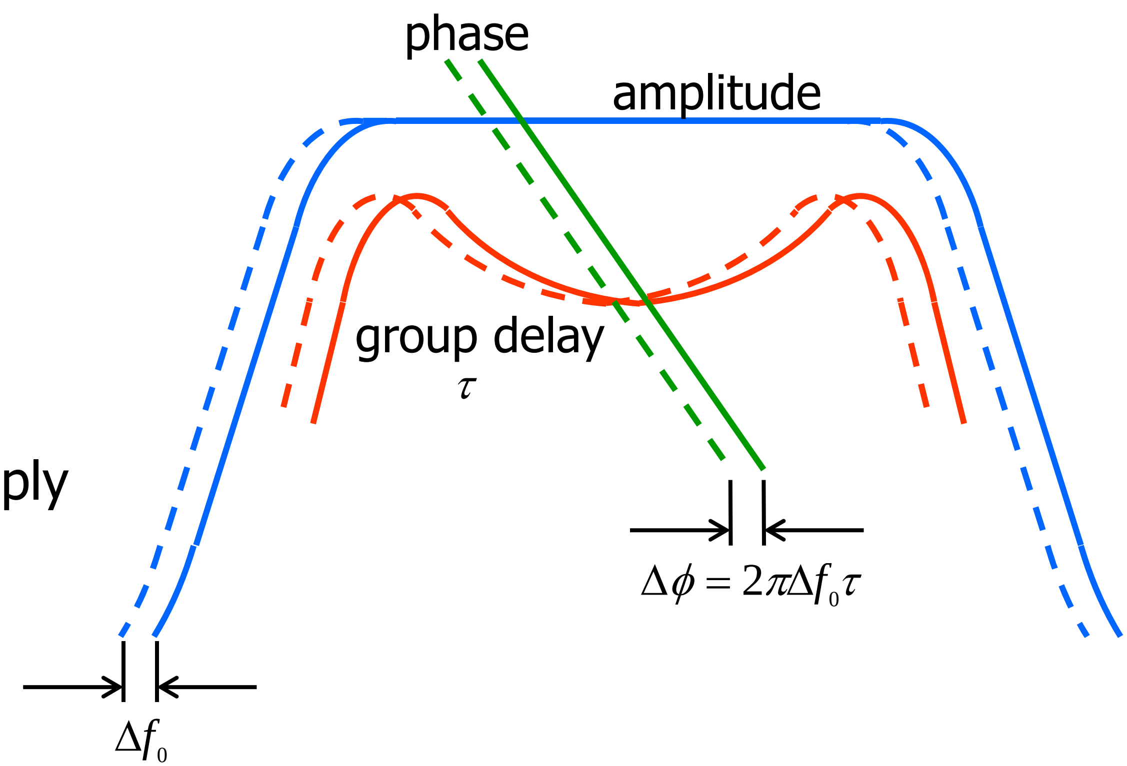
$$S_g = \frac{G_{RMS}^2}{\Delta f} = \frac{f^2 S_\phi}{f_0^2 \Gamma_f^2} = \frac{S_\phi}{\Gamma_\phi^2}$$

Group Delay in Filters

- Filters can either be characterized in terms of fractional frequency sensitivity or phase sensitivity
- In the latter case

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

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



Intermittent Contact

- 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 or cables
  - covers
- Bandwidth of intermittent contact can be very broad
  - well beyond the input vibration bandwidth

Vibration Isolation

Discrete

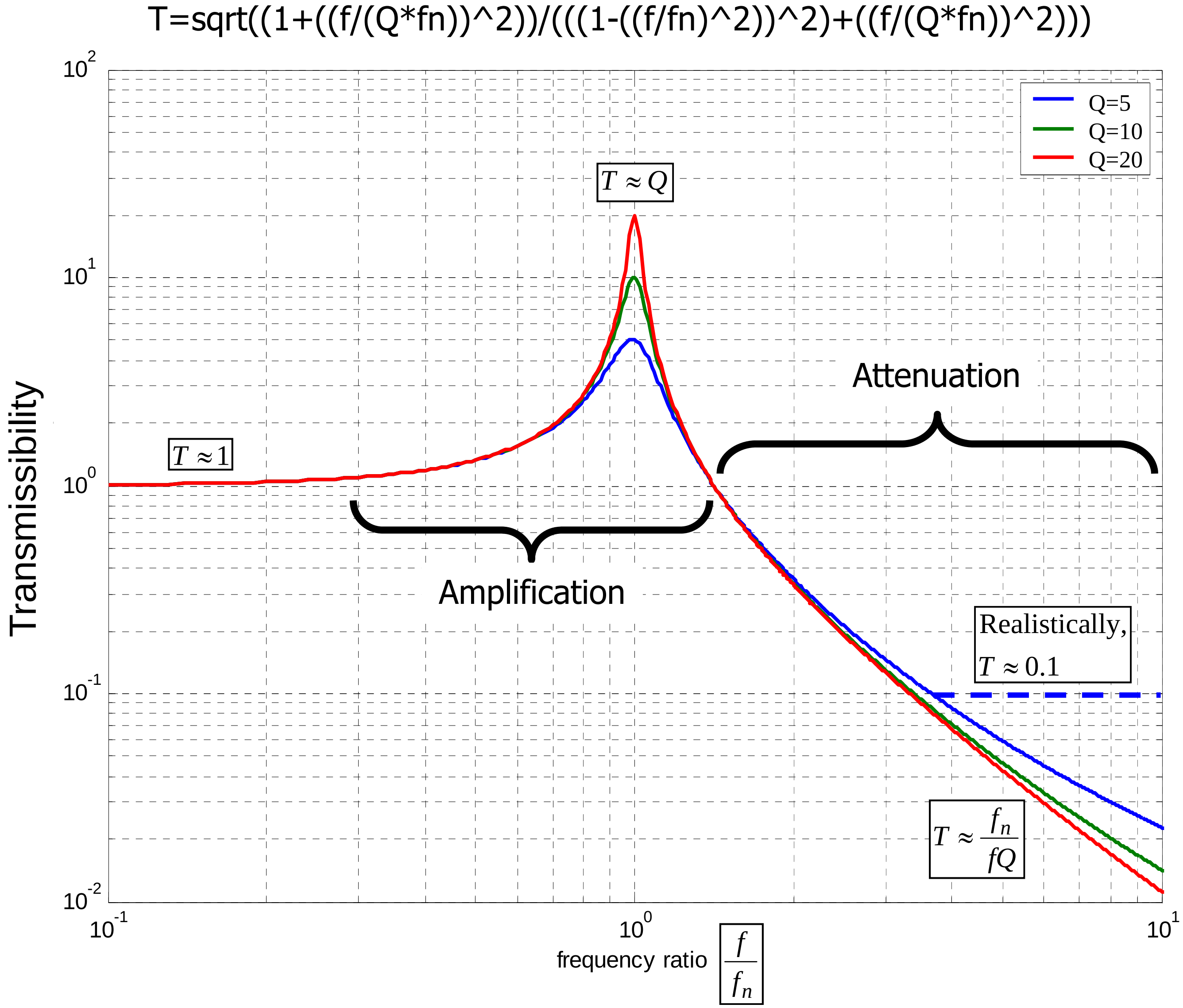
$G_{out}=TG_{in}$

overall $\leq \Sigma|G_{out}|$

Broadband

$S_{out}=T^2S_{in}$

overall = $\sqrt{\Sigma[S_{out}\Delta f]}$



Other Vibration Level Reduction Techniques

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- Careful design of structure
  - High natural frequency (stiff and light)
    - Lower displacement and often lower excitation
    - Enclosures make lousy vibration isolators
  - Octave of separation between 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
- Active control systems: use an actuator to cancel the vibration

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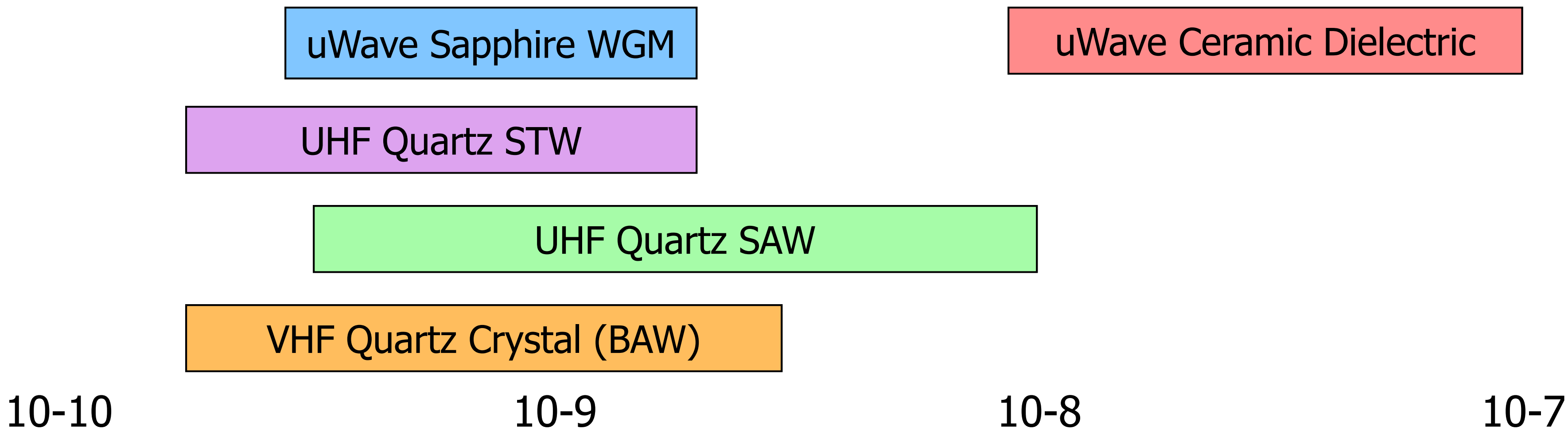
Section 3:

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/STW resonators results from vibration-induced stress in the crystal plate.
- Resonant frequency change in Dielectric and Whispering Gallery Mode (WGM) resonators results from vibration-induced dimensional change in the resonator assembly.

Vibration: An Example

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- 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 quite small:

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

This level is typically exceeded in an office building!

Methods for Reducing Oscillator/Resonator Vibration Sensitivity

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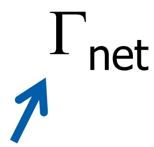
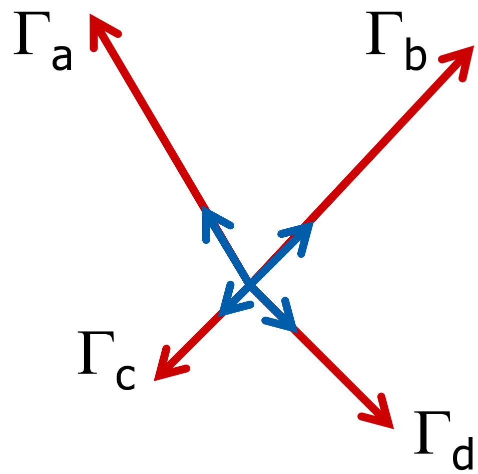
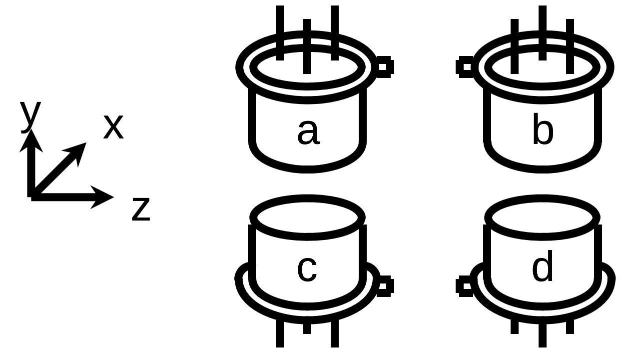
Least Costly	Use of multiple, unmatched oppositely-oriented devices.
↓	Reduction of resonator vibration sensitivity via resonator design (geometry, mounting, mass loading, etc.).
	Cancellation via feedback of accelerometer-sensed signals to the oscillator frequency tuning circuitry.
Most Costly	Measurement of individual (crystal) resonator vibration sensitivity magnitude and direction and use of matched, oppositely-oriented devices.

Use of Multiple Resonators and/or Vibration Isolation



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





- 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 vector 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 ΔF/N for the N series combination.

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

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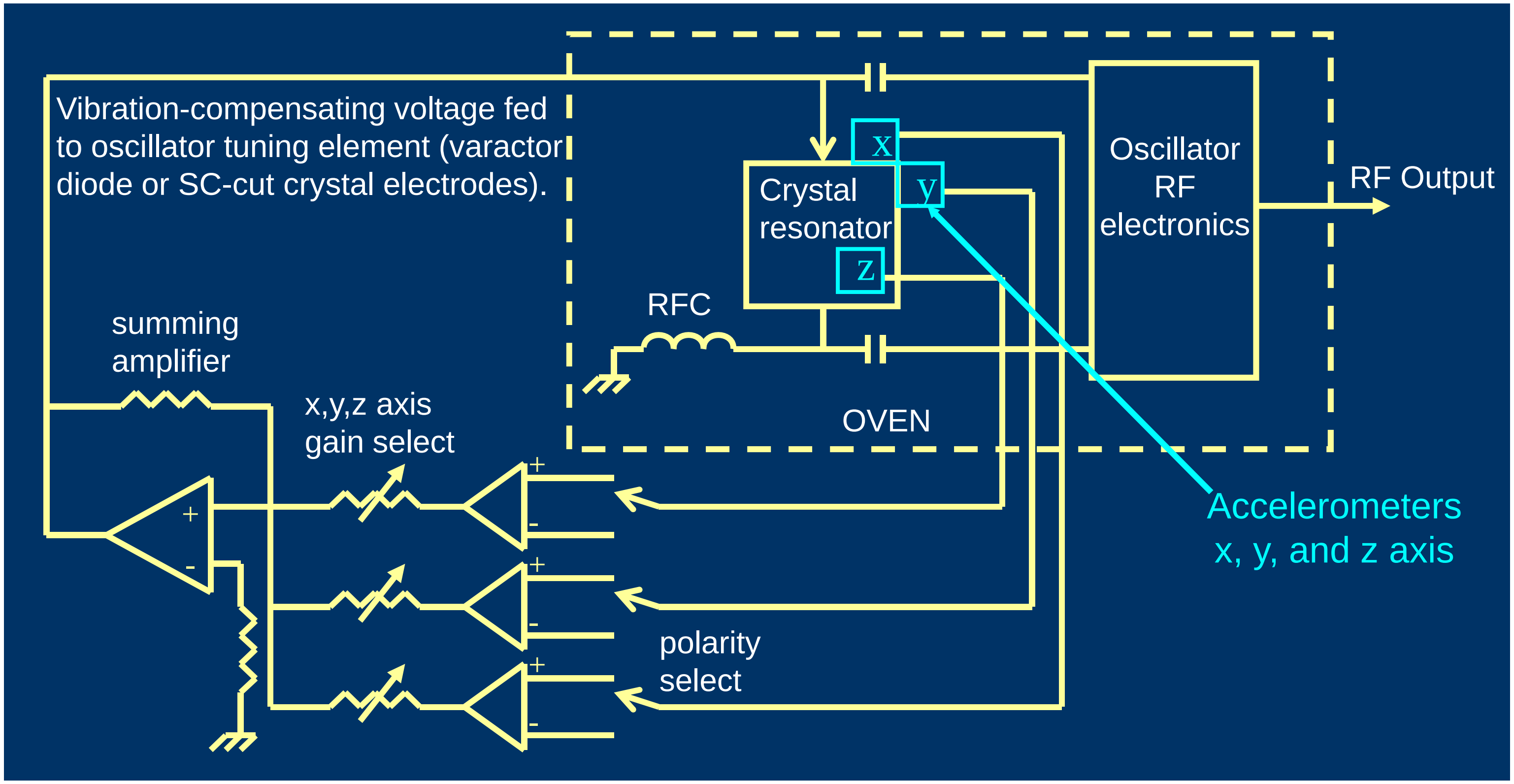

- Vibration produces a voltage from the accelerometers that is appropriately amplified and fed back to the oscillator frequency tune control element.
- Tuning can be via use of varactor diodes in series with the resonator or, in the case of an SC-cut crystal, can be applied directly across the crystal 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

Vibration-Induced, Oscillator Phase Noise Degradation Remains Substantial

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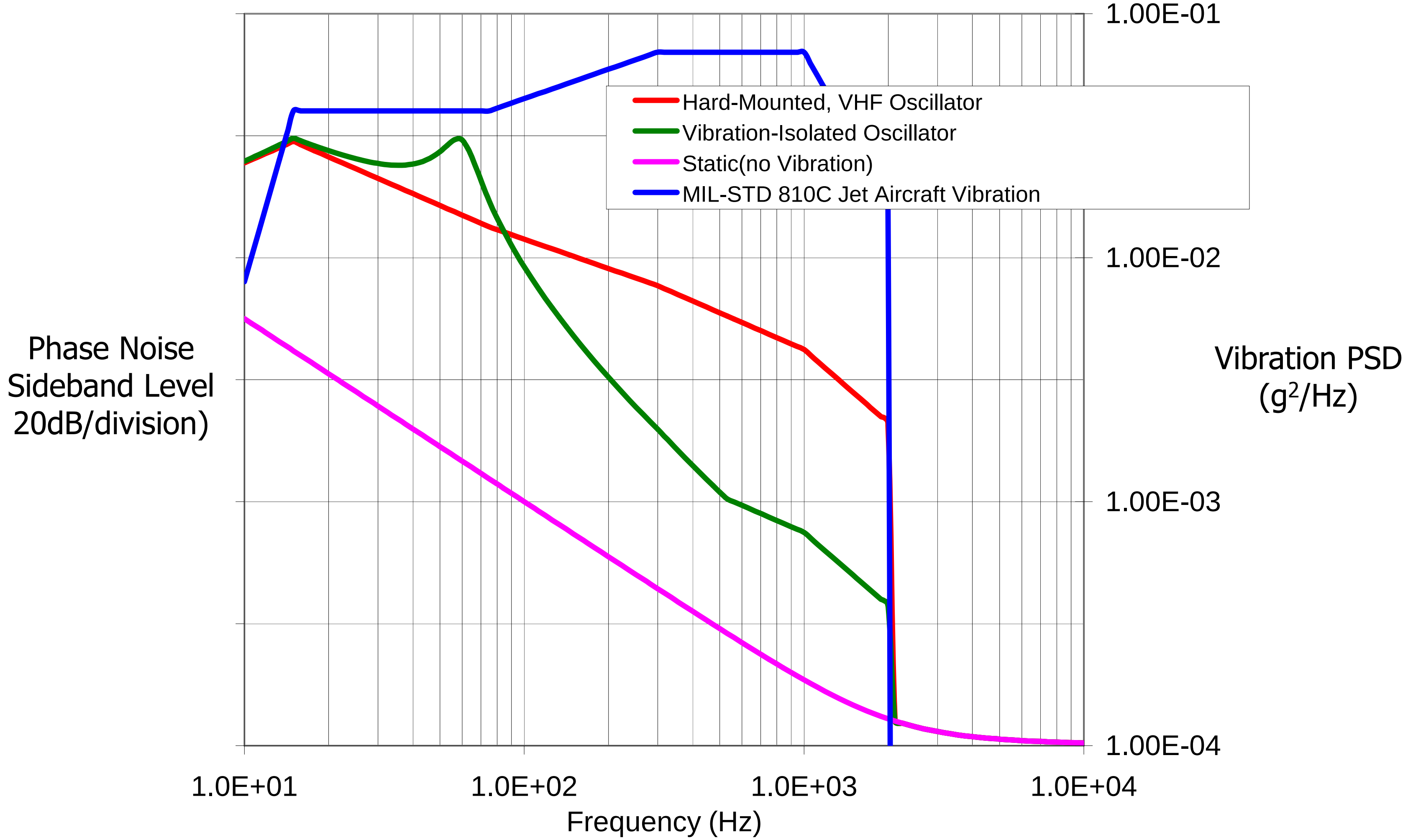

In spite of excellent vibration immunity and even using mechanical vibration isolation, phase noise degradation is substantial (20-40dB) for commercially available, low noise oscillators

Vibration-Induced Phase Noise in Non-Oscillator Components

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- 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 carrier offset frequencies.

Oscillator Equivalent Fractional Frequency Vibration Sensitivity*

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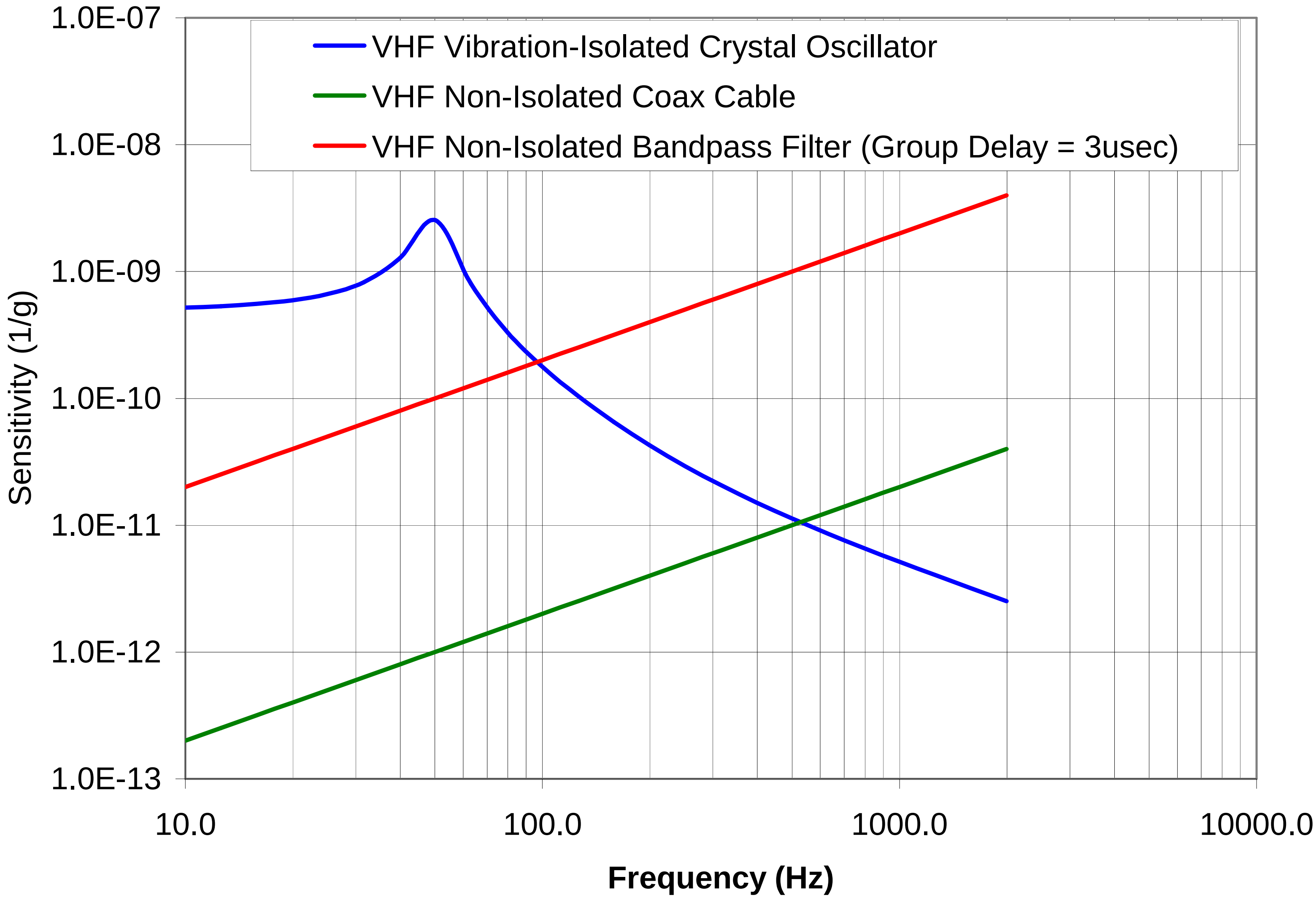

* Notional data

Selection and Packaging Guidelines for Non-oscillator Components

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- Components which require adjustment should be avoided or cemented after tuning.
- If possible, avoid use non-potted and non-shielded inductors.
- If possible, avoid very high circuit impedances sensitive to capacitance variation due to enclosure cover or printed board motion.
- Ensure hut and module covers are sufficiently stiff and provide the greatest practical headroom so as to minimize the capacitance variation.
- Apply damping material to module covers that contribute capacitance to phase-noise sensitive RF circuitry.
- Avoid unnecessarily narrow band filters
  - the most inherently vibration sensitive, non-oscillator component
  - often implemented with high Q resonators

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

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- Cable sensitivity
  - Semi-rigid cable is least sensitive to vibration.
  - Some flexible cable are better than others (you get what you pay for).
  - Solid or wrapped cable shields are better than braided shields.
  - Low sensitivity, flexible cables are required for connections to 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.

Section 1:

Phase Noise Measurement

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

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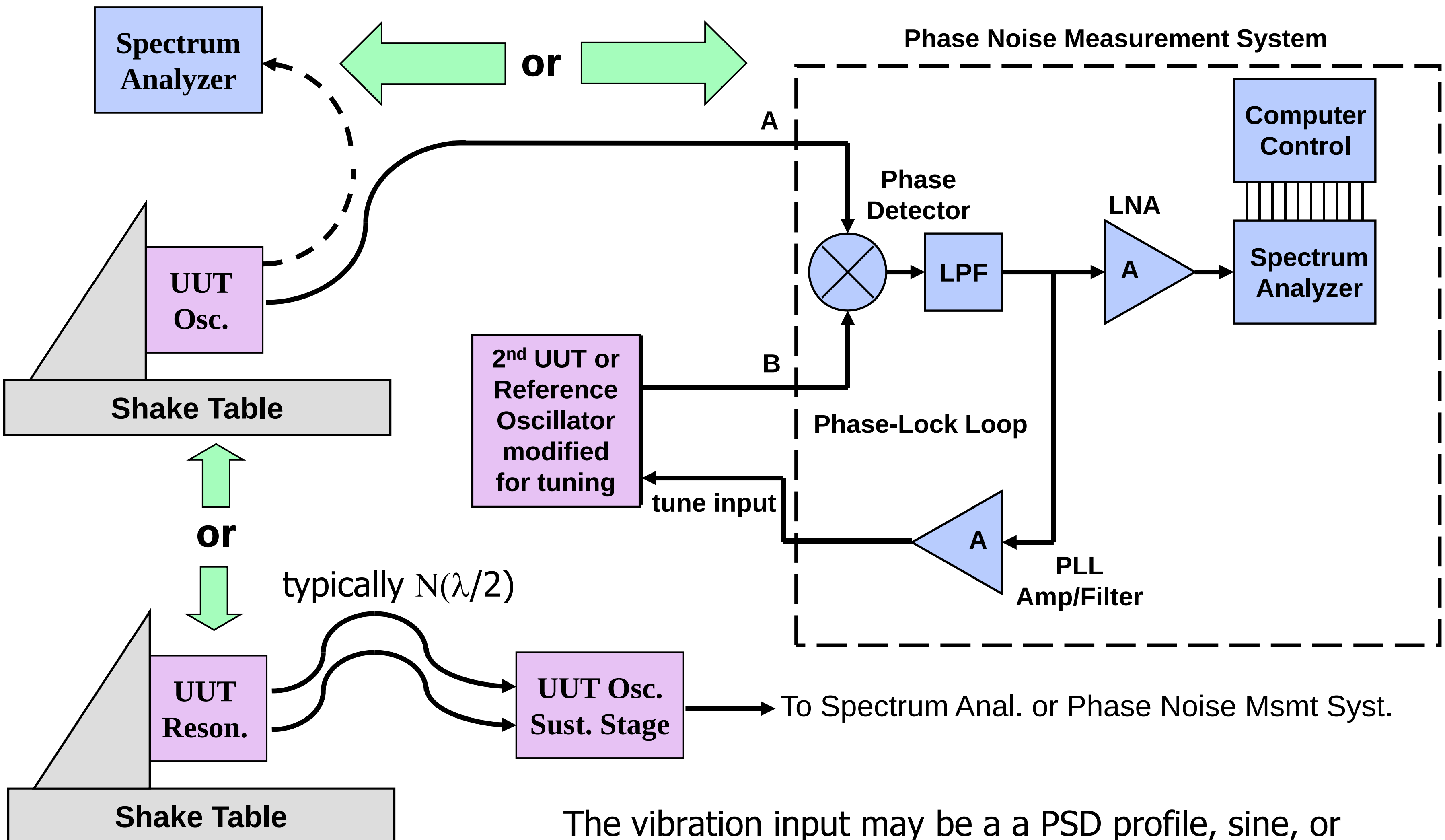
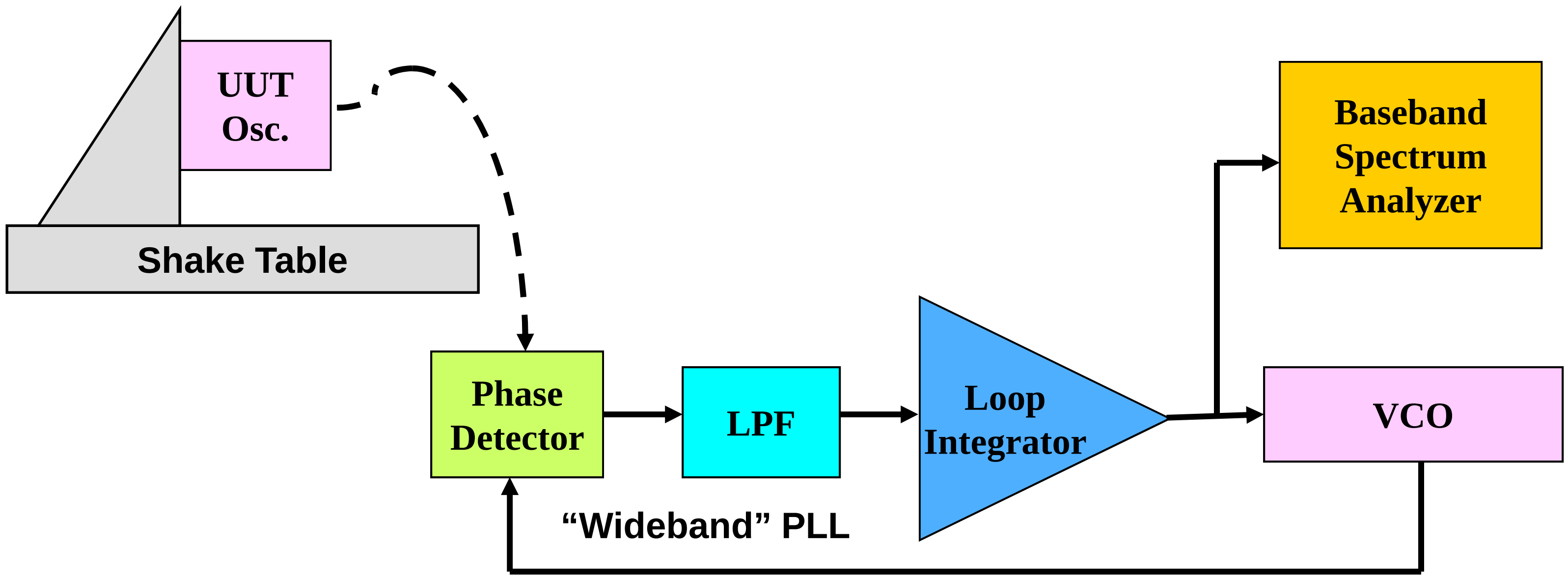
Method Number	Device Under Test (on shaker)	Measurement Method	Comments
1.	Entire oscillator	Absolute phase noise at the PLL phase detector.	Requires two, phase-locked oscillators.
2.	Entire oscillator	Measurement of phase-locked oscillator tuning voltage.	Requires a PLL bandwidth in excess of the maximum vibration frequency.
3.	Oscillator resonator(s)	Two oscillator measurement with coaxial cable connecting resonator(s) to sustaining stage. Narrowband filter sensitivity may be evaluated by using the UUT filter as an oscillator frequency control element.	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.	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 a PSD profile, sine, or swept-sine.

Alternative Measurement of Oscillator or In-oscillator Resonator Vibration Sensitivity

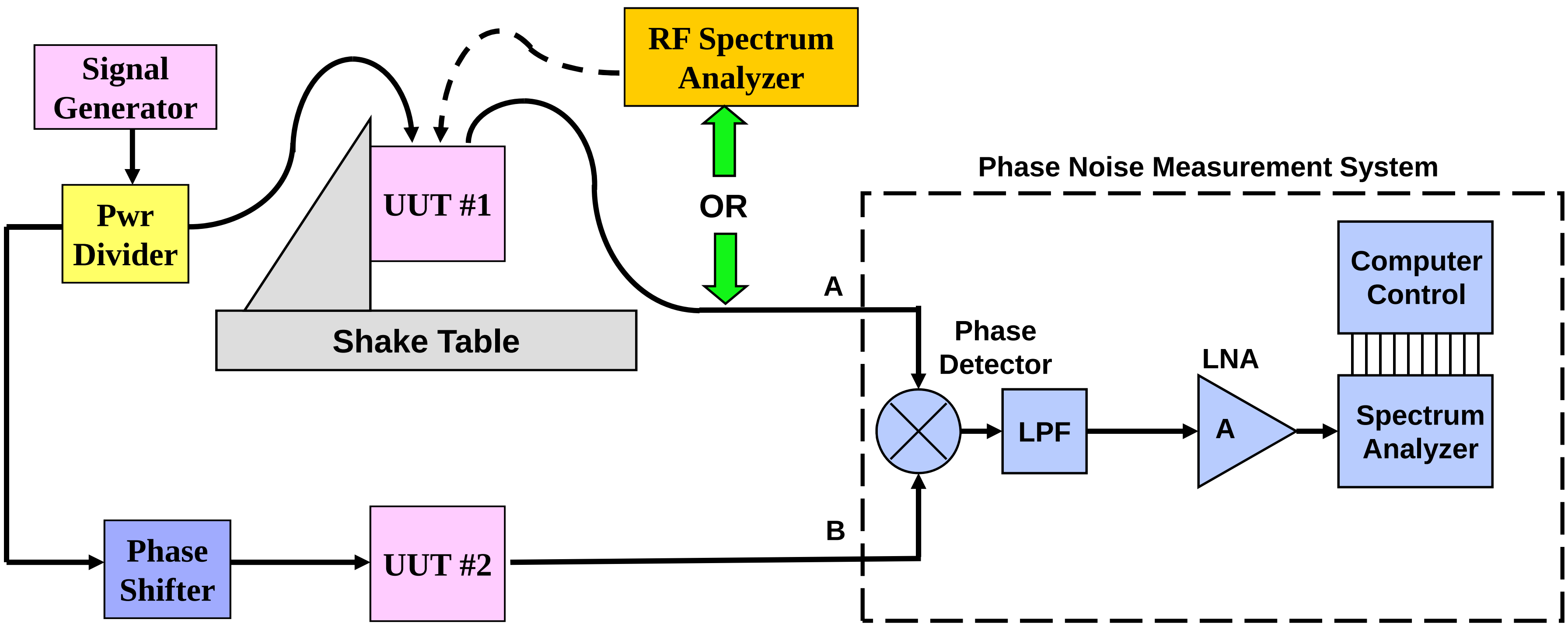


- The VCO is selected for high modulation rate capability and tuning sensitivity. Inside the PLL bandwidth, the VCO tuning voltage spectrum is a measure of the VCO plus UUT oscillator FM noise plus the vibration-induced frequency change in the UUT oscillator. The PLL acts like a frequency discriminator.
- 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.

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) insufficiently high, compared with circuit static FM noise.

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.

Factors Affecting Non-Oscillator Vibration-Induced PM Measurement Accuracy

- Vibration-induced PM in the coaxial cables traversing the shaker/test equipment interface.
- Mechanical resonances in the vibration fixture or UUT assembly.
- 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.
- Insufficiently low signal generator PM noise in combination with large differences in the phase bridge signal path delay.
- Insufficient 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 PM sideband levels) insufficiently high, compared with circuit static PM noise.

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

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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.

Factors Affecting Multi-Function Assembly Vibration-Induced FM and PM Measurement Accuracy

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- Vibration-induced PM in the coaxial cables traversing the shaker/test equipment interface.
- Mechanical resonances in the vibration fixture.
- Mechanical non-linearity. Cable and subassembly surfaces scraping or hitting under vibration. This can result in vibration-induced phase noise well in excess of the maximum vibration frequency.
- Insufficiently low signal generator PM noise in combination with large differences in the phase bridge signal path delay.
- Insufficient 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 PM sideband levels) insufficiently high, compared with circuit static PM noise.

Bandwidth Issues

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- Definition Bandwidth
  - Standard measures of noise in the frequency domain (i.e., **$\mathcal{L}$**(f), S_ϕ(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

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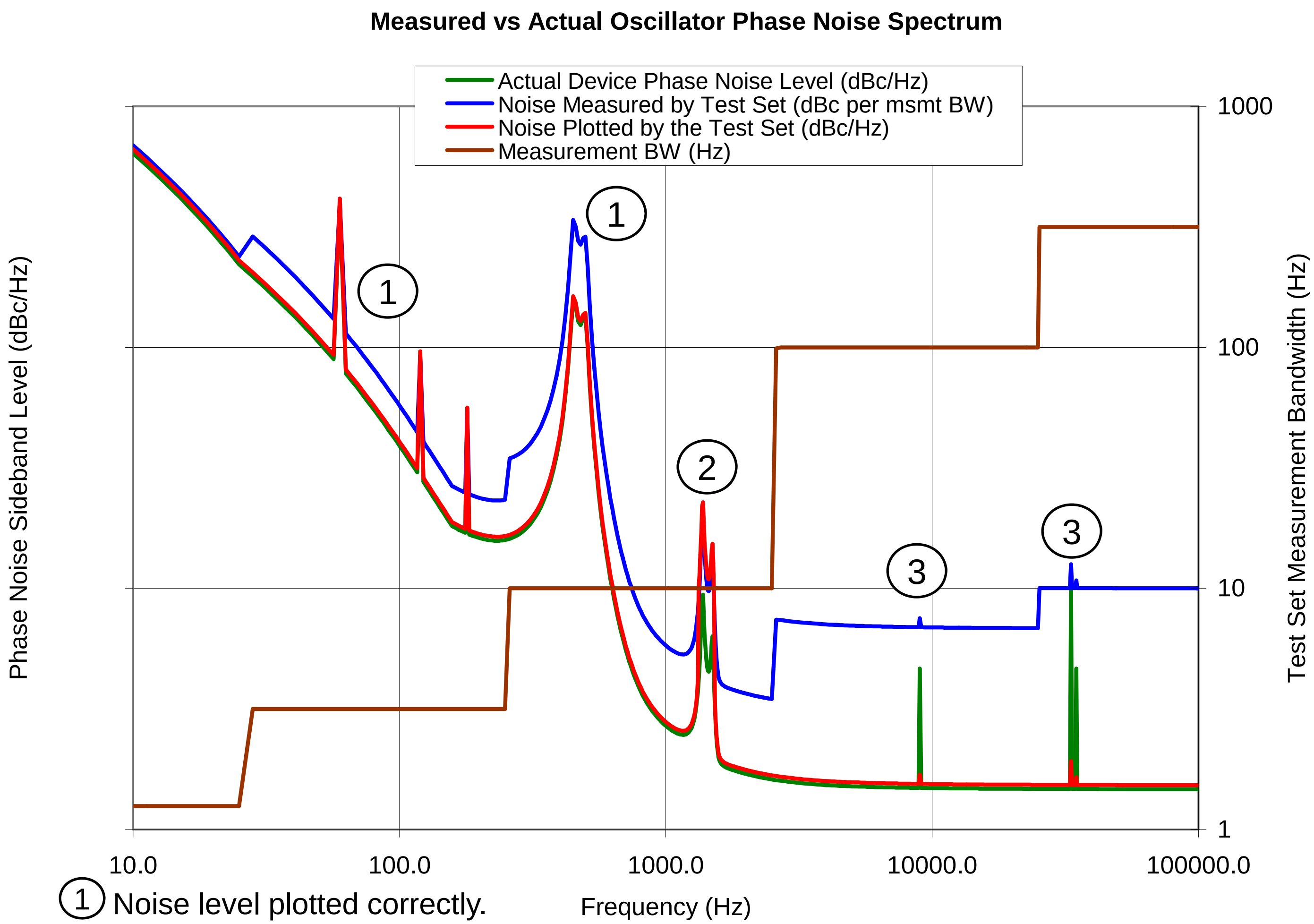

① Noise level plotted correctly.

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.

Troubleshooting Techniques

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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.

Section 2:

Vibration Testing

Typical Vibration Test Setup

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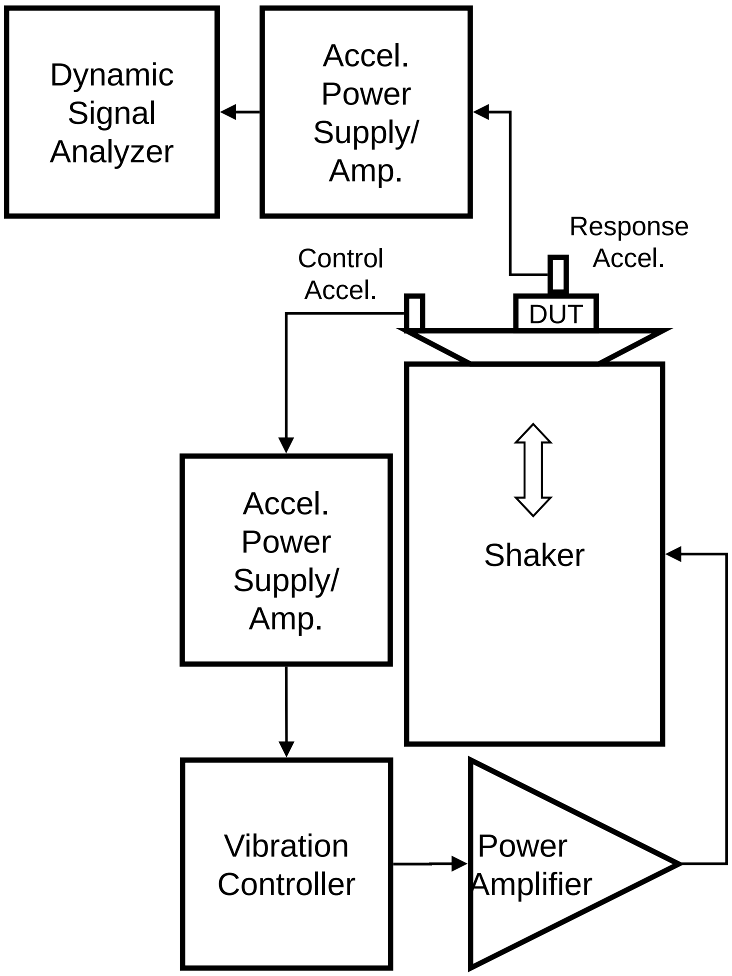
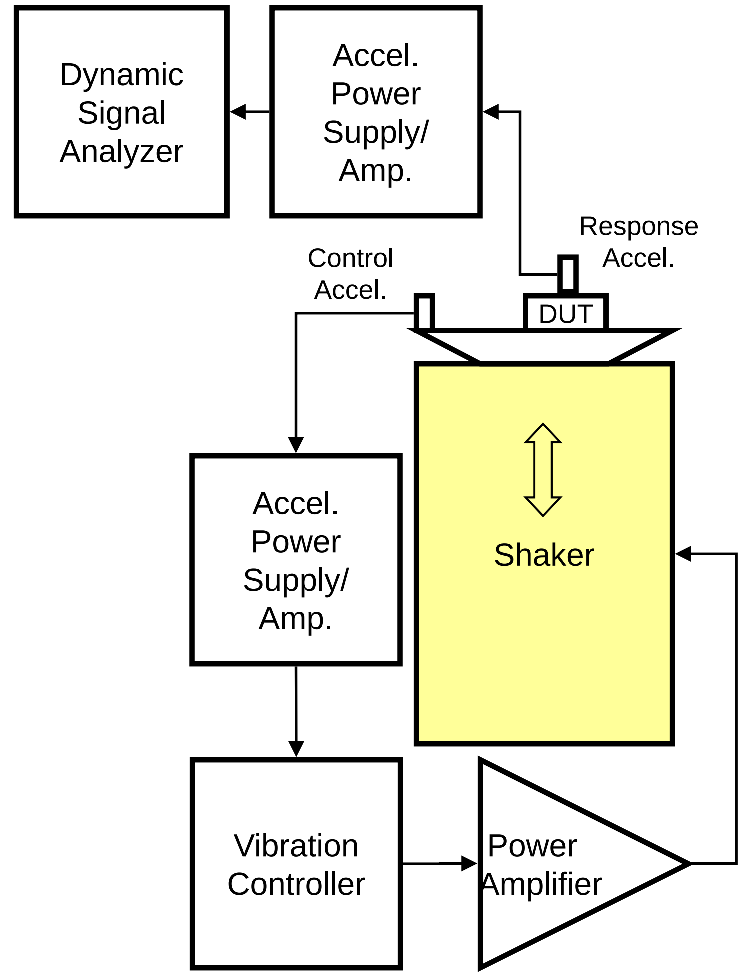
- Types of vibration supported
  - Discrete
    - Sine(s) dwell
    - Swept/stepped sine
  - Broadband
    - White noise random
    - Colored/shaped spectra
  - Combinations of discrete and broadband
  - Transient (shock)
    - Not common for phase noise testing
- Constant acceleration not supported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



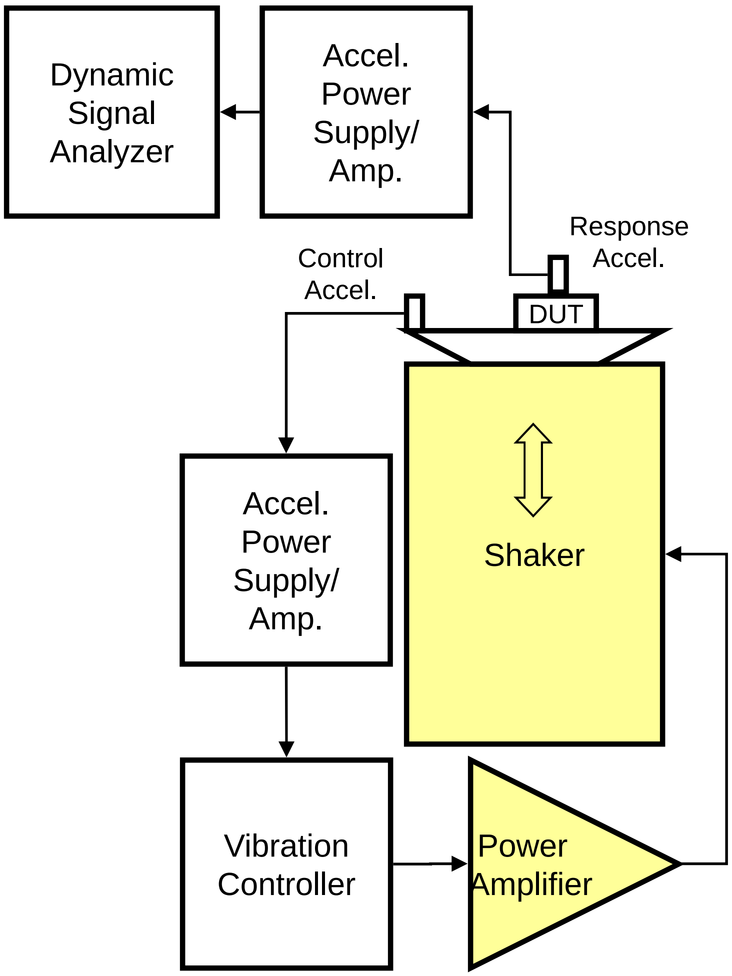
Shakers and Axes

- 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



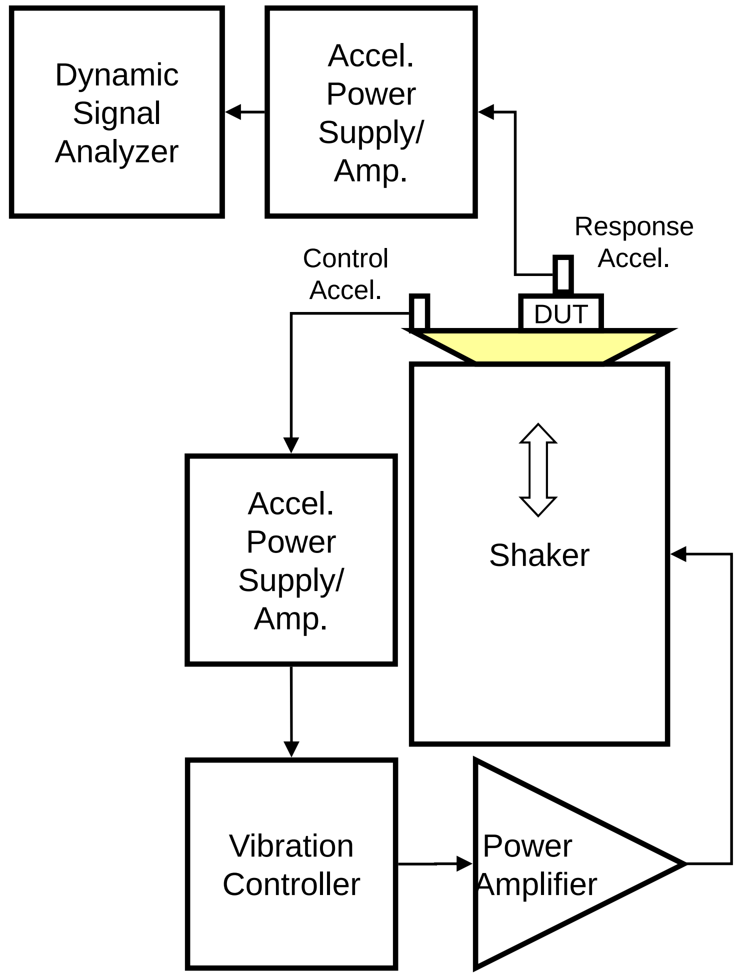
Vibration Level Limitations

- 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



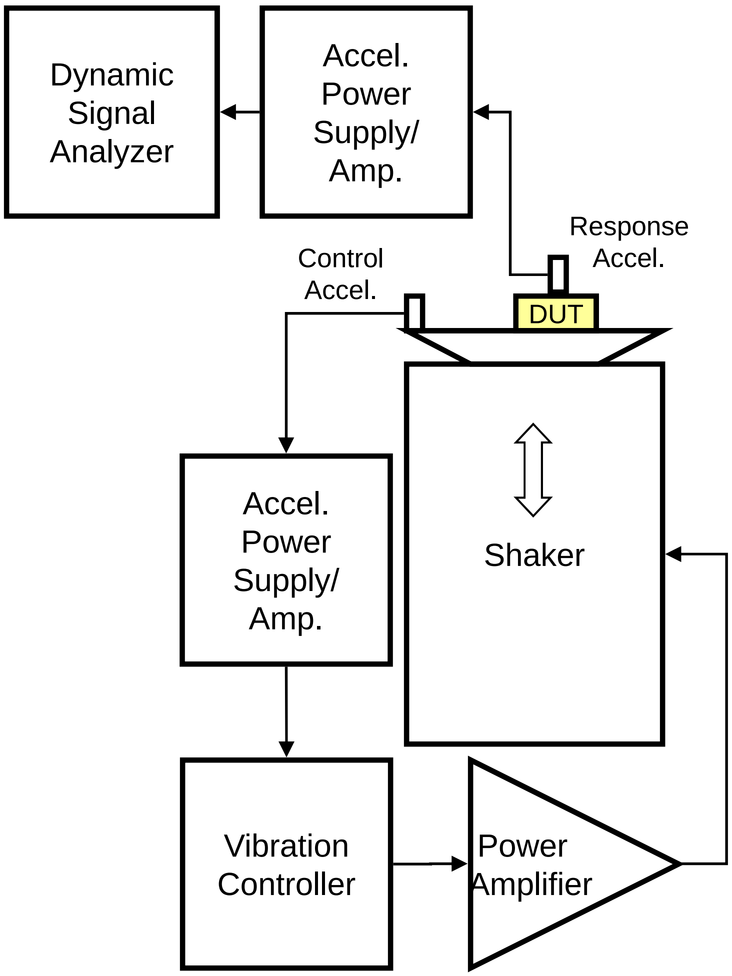
Fixtures

- 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



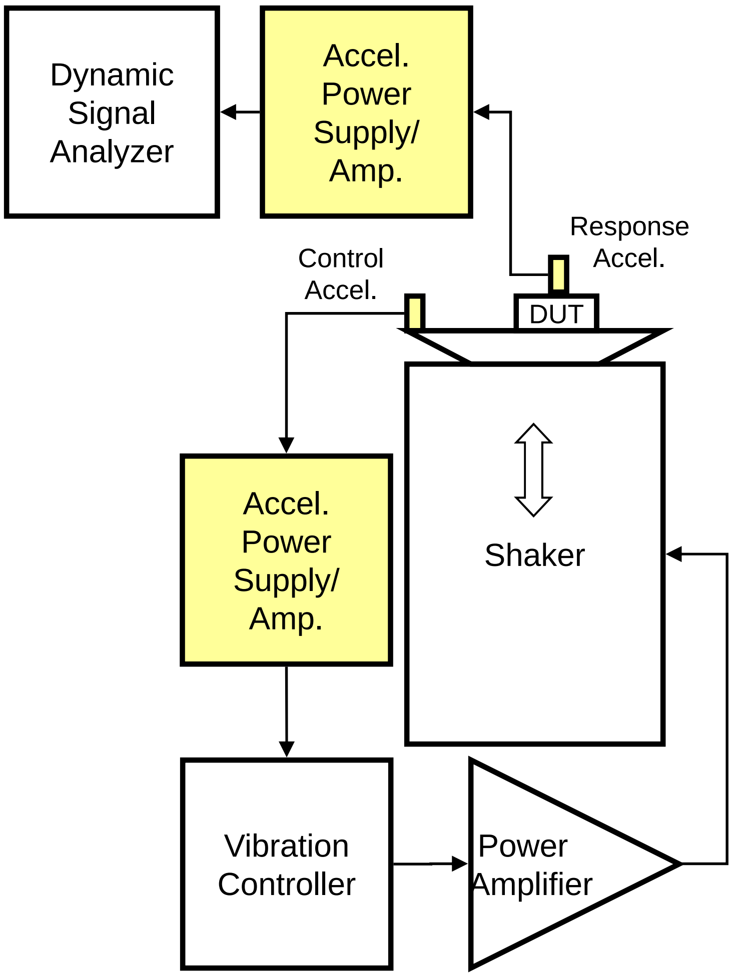
Configuration of the DUT

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



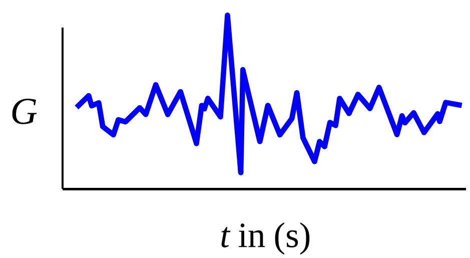
Sensors

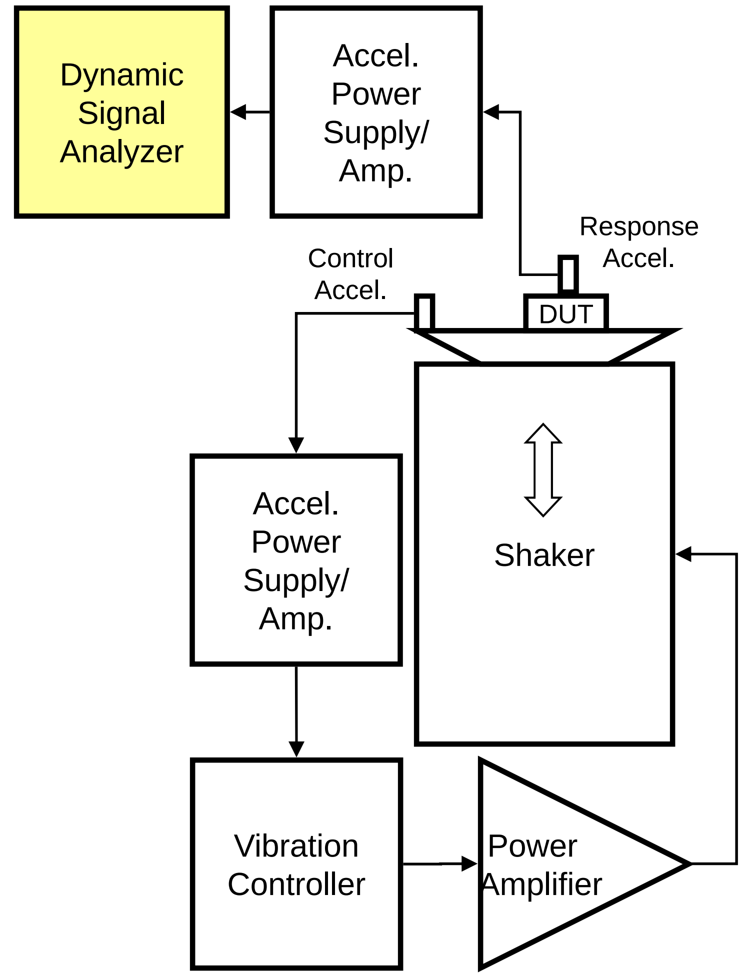
- Piezoelectric accelerometers
  - Cannot measure very low or very high frequencies
- Other accelerometers
  - Can measure very low frequencies
- Laser Doppler Velocimeter
  - non-contact velocity measurement
  - single-point or scanning
- Displacement sensors
  - Contacting
    - LVDT
    - Potentiometer
  - 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
- May indicate intermittent noise





Frequency Domain Analysis

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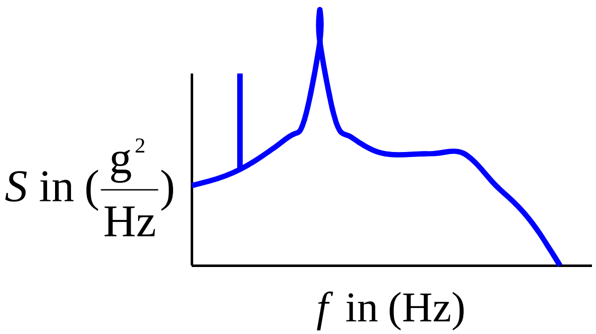
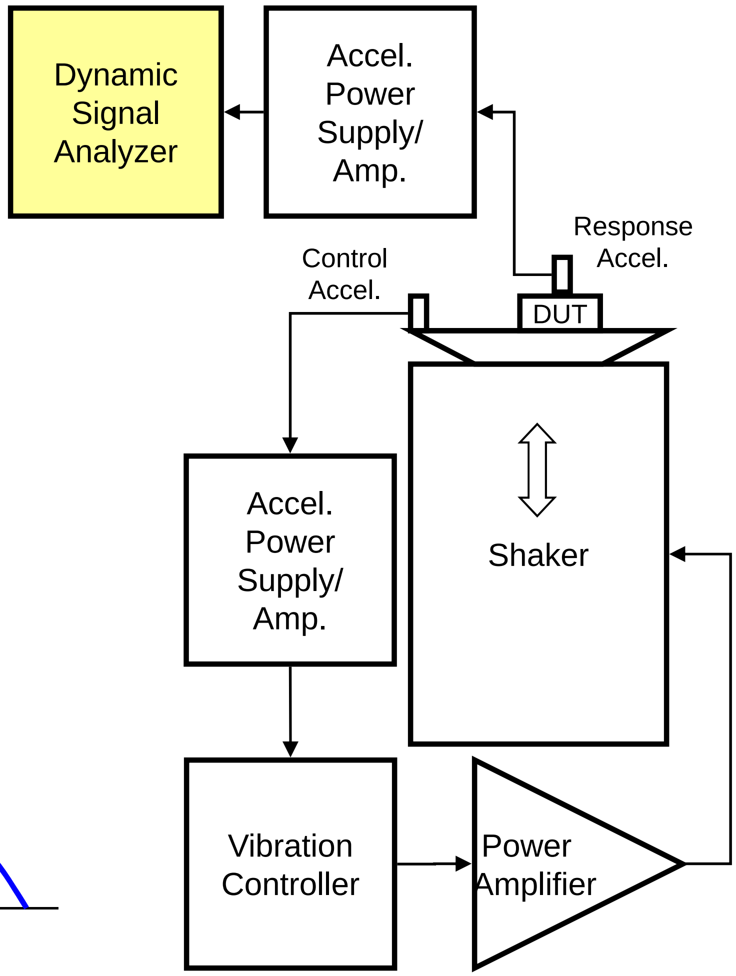
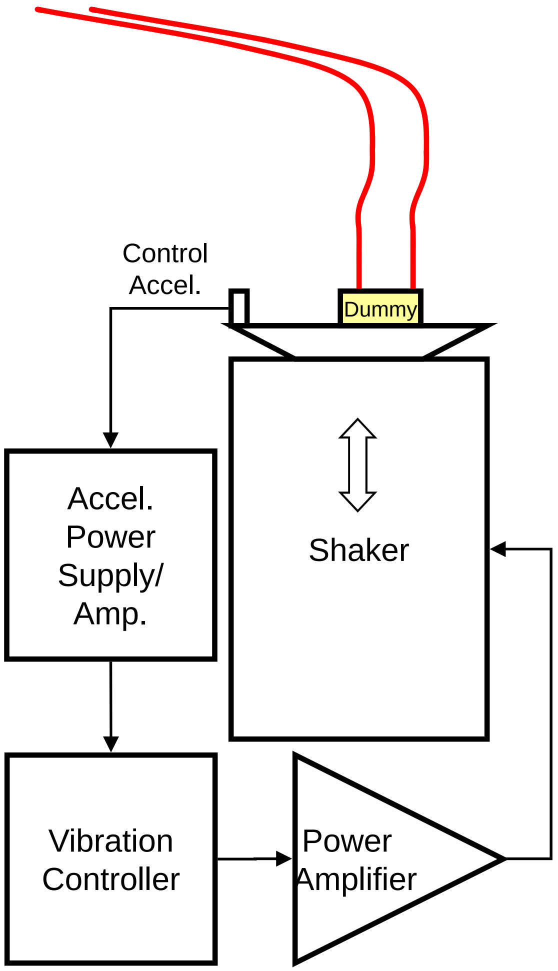
- Best for comparison to phase noise spectra
- Obtained via Fourier transform
- Several PSDs averaged to remove uncorrelated noise
- Gives clear indication of
  - Discretes
  - Resonances
  - Overall level





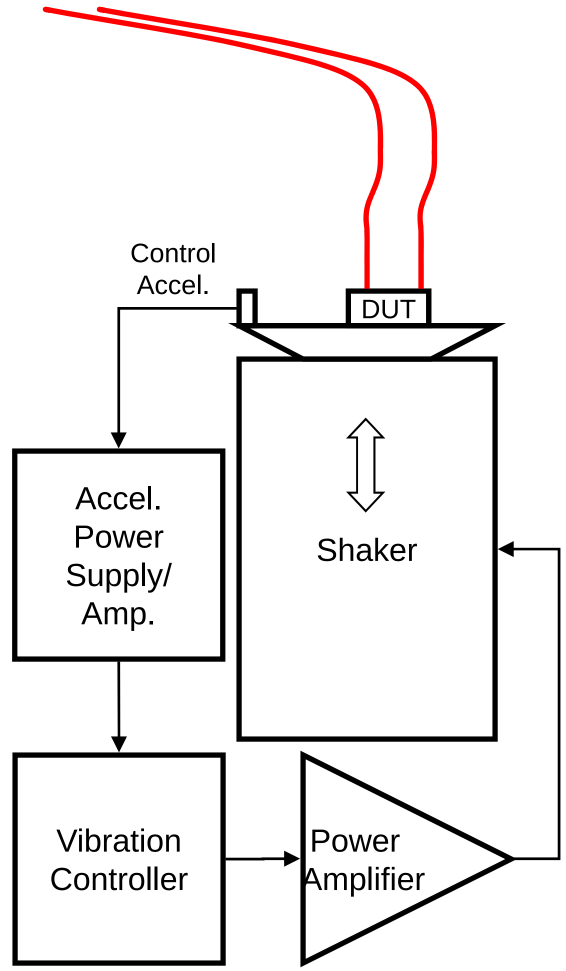
Baseline Calibration

- Baseline Calibration
  - 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 daily



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

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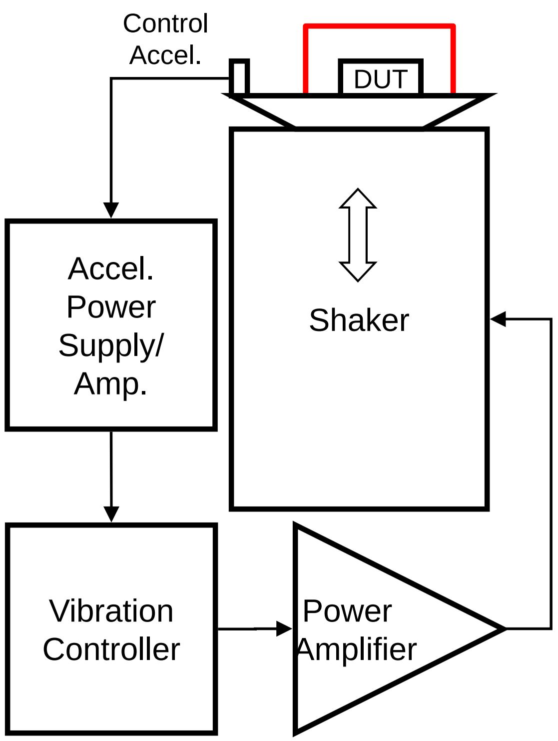
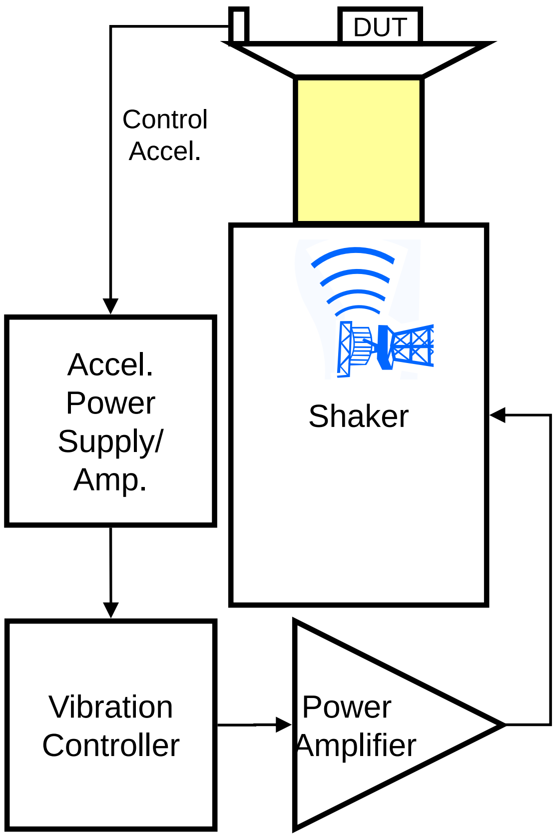
- Acoustic noise generated by shaker
  - Can be quantified by disconnecting DUT from shaker but keeping it close
  - Separate test-set from shaker
- Acoustic noise generated by blowers, etc.
  - Often produce spurious noise
  - Enclose blowers and run long hoses
  - May be able to turn off for a short time
- Enclosing DUT is an option



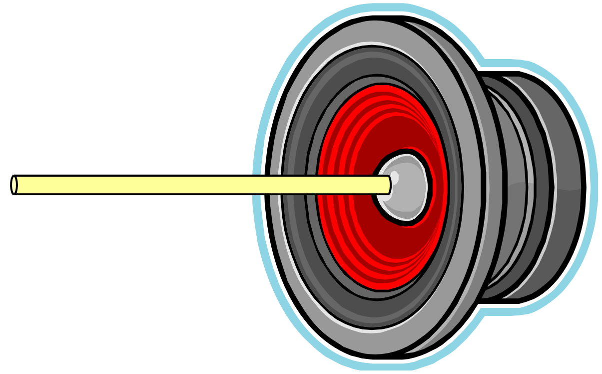
EMI

- 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"
    - Effect can be quantified by disconnecting DUT from shaker but keeping it close
  - Increasing 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 from the shaker/fixture
  - Place test-set on a separate AC circuit from vibration test equipment

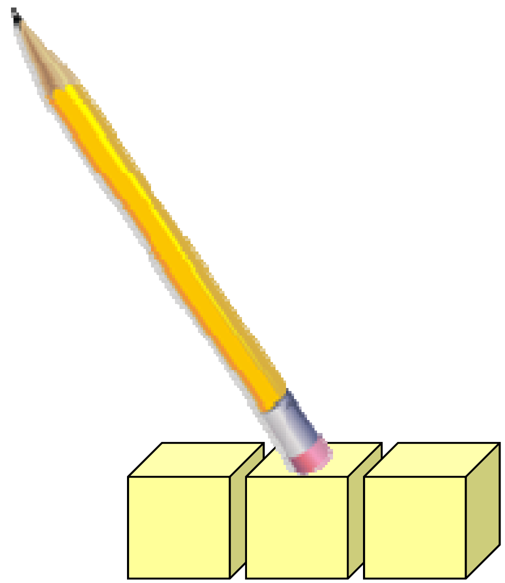


Methods of Locating Sensitive Components

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

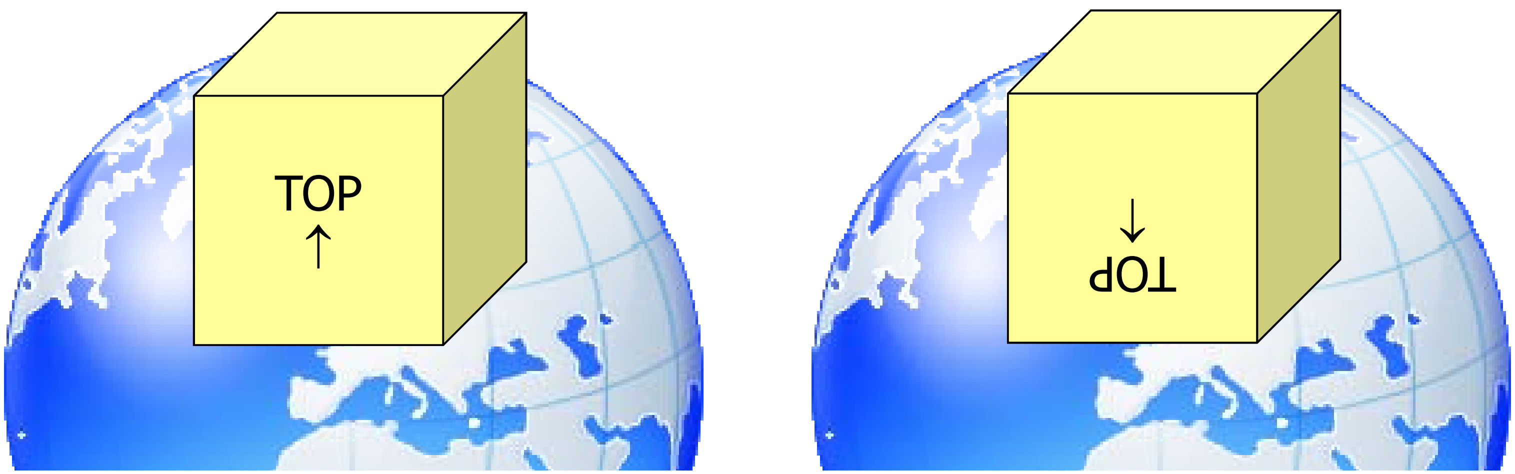


- Selective immobilization
  - Fingertip or pencil eraser



Tip-Over Test

- Some components are sensitive enough to measure the phase noise due to gravity
- In such cases, one can vary the acceleration from +1 g to -1 g by "tipping over" the component



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