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[vibration / acoustics]



Vibration Control

Eric E. Ungar, Sc.D., PE
Acentech Incorporated

Hal Amick, PE
Colin Gordon & Associates

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Vibration Control - Outline

- How Vibrations are Characterized (EEU)
- The Role of the Advanced Technology Bldg. (EEU)
- Vibration Measurements (HA)
- Effects of Vibrations on Instruments (HA)
 - Example – Microscope
 - Generic Vibration Criteria
- Reducing Vibrations within the Building (EEU)
- Reducing Vibrations at the Instrument (HA)
 - Internal Isolation
 - External Isolation

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How Vibrations are Characterized

The Role of the Advanced Technology Bldg.

Eric E. Ungar, Sc.D., PE
Acentech Incorporated

Vibration Definitions

Eric E. Ungar

- **Vibration:**
Back-and-forth motion about an equilibrium position
- **Most Important in Buildings**
Vertical – Due to interior and nearby disturbances
Horizontal – Due to seismic activity and wind
- **Ground motions often reported in Peak Particle Velocity (PPV)**
PPV = Greatest value of 3-D (triaxial) vector amplitude in some observation period

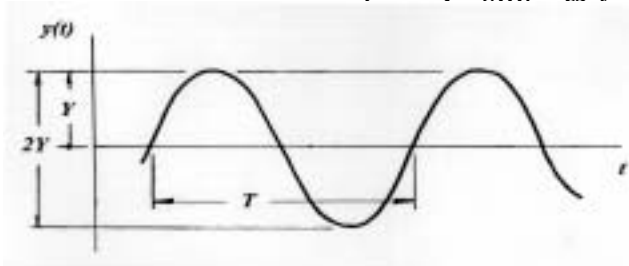
Generally we need more detail

Sinusoidal Vibrations: Amplitudes

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- Conceptually simplest vibration is sinusoidal or "simple harmonic"

$$v = Y \sin(\omega t + \phi)$$



Y = Amplitude (Zero-to-Peak)

$2Y$ = Double Amplitude (Peak-to-Peak)

T = Period [sec]

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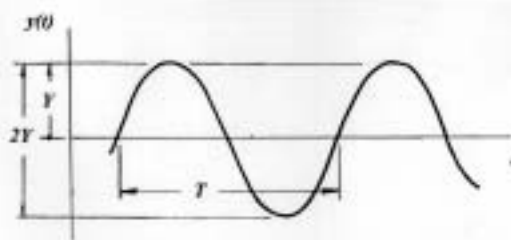
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Sinusoidal Vibrations: root-mean-square

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f = frequency [cycles/sec = Hz] = $1/T$

ω = radian frequency [radians/sec] = $2\pi f$



Root-mean-square (rms) value =

$$y_{rms} = \left[\frac{1}{T} \int_{t_0}^{t_0+T} y^2(t) dt \right]^{1/2} = \frac{Y}{\sqrt{2}}$$

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Vibration metrics: displacement, velocity, acceleration

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If $y(t)$ is a displacement,

$$y(t) = Y \sin(\omega t + \phi)$$

Velocity:

$$v(t) = dy/dt = Y\omega \cos(\omega t + \phi) = V \cos(\omega t + \phi)$$

Acceleration:

$$a = dv/dt = -V\omega \sin(\omega t + \phi) = -A \sin(\omega t + \phi)$$

Amplitude relations:

$$V = Y\omega \quad A = V\omega = Y\omega^2$$

where: $\omega = 2\pi f$

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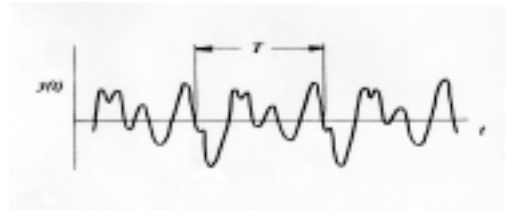
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Periodic Vibrations

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- Practical vibrations are rarely simply sinusoidal
- Fourier analysis: sum of sinusoidal components

$$y = \sum_{n=1}^{\infty} Y_n \sin(\omega_n t + \phi_n) ; \quad \omega_n = n\omega_1$$



- If motion repeats after each interval T (the "Period") it is called "periodic"; otherwise it is called "complex"

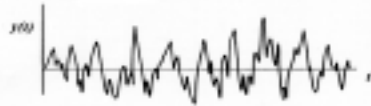
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Random Vibrations

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- Vibration is "deterministic" if value at any future time can be predicted from past history
- Vibration is "random" if it is unpredictable, except statistically. Random vibrations are "stationary" if the statistics do not change with time.



- In Buildings:
 - Machinery: deterministic, often periodic, usually complex
 - Background: random, stationary in some intervals
 - Activities: transient pulses

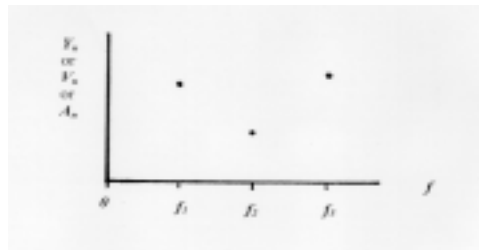
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Vibration Spectra

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- "Spectrum" = Frequency distribution of amplitudes
- For spectrum of periodic motion, use Fourier analysis



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Vibration Spectrum – Random Motion

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- For spectrum of *random* motion

Assume that the motion observed during a recording interval T_R repeats continually, and apply Fourier analysis to that interval

$$Y_n = \frac{1}{2T_R} \int_{-T_R}^{T_R} y(t) \sin n\omega_1 t \cdot dt \quad \omega_1 = 2f_1 = 2\pi/T_R$$

Amplitudes Y_n depend on record length T_R . We need specify it or equivalent information, such as the “analysis bandwidth”

$$\Delta f = f_i / (\text{number of spectrum “lines”}); \quad f_i = 1/T_R$$

Note: if T_R is doubled, we get twice as many components. Old Y_n 's then are half as large.

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Power Spectral Density (PSD)

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- “Power spectral density” normalizes spectra in relation to bandwidth

$$PSD(f_j) = \frac{(y^2)_{avg, \Delta f_j}}{\Delta f_j}$$

f_j = center frequency of band Δf_j

Mean square velocity in band is independent of bandwidth

$$(y^2)_{avg} = \frac{1}{2T_R} \int_{-T_R}^{T_R} y^2(t) dt = \sum Y_n^2$$

Units of *PSD*: m^2/Hz or $(in/sec)^2/Hz$, etc.

Root(PSD) has units of m/\sqrt{Hz} or $(in/sec)/\sqrt{Hz}$

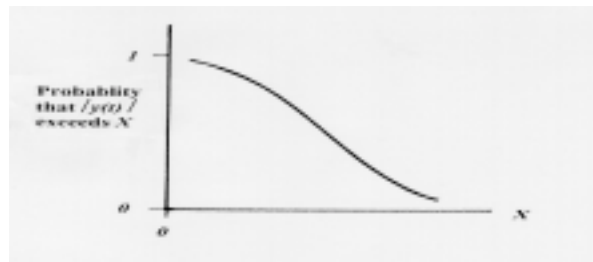
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Vibration Statistics

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- Stationary random vibrations may also be characterized in terms of probability distributions:



- Probability magnitudes for levels are often stated in terms of “percentile levels”, e.g.,
 L_{10} =Level that is exceeded 10% of the time

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Levels and Decibels

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- Sound = Vibration of Air Pressure
May cause internal vibrations in sensitive equipment
- Levels and Decibels (dB)

Vibration Velocity Level = L_v

$$L_v (dB) = 10 \log_{10} \left[\frac{v_{rms}^2}{v_{ref}^2} \right] = 20 \log_{10} \left[\frac{v_{rms}}{v_{ref}} \right]$$

Sound Pressure Level (SPL) = L_p

$$L_p = 20 \log_{10} \left[\frac{p_{rms}}{p_{ref}} \right]$$

>> The reference values v_{ref} and p_{ref} must be stated

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Vibration Basics - Summary

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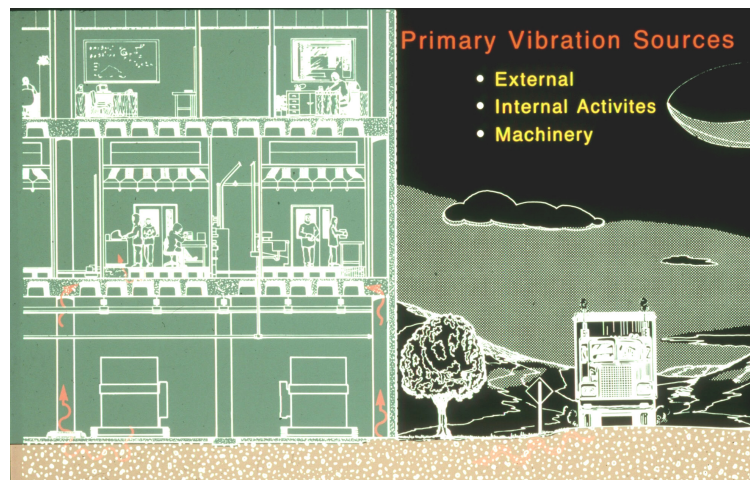
- **Sinusoidal vibrations**
Displacement, velocity, acceleration relations
Amplitudes, root-mean-square
- **Periodic vibrations: Spectra**
- **Random Vibrations**
Spectra and Power Spectral Density (PSD)
Probability distributions
- **Levels and Decibels**
- **NEXT: Relevance to Buildings**

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Typical Vibration Sources in a Building

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Vibration Sources

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- Vibrations of sensitive instruments may be caused by ...
 - Locally induced floor vibrations
 - Vibrations transmitted from elsewhere
 - Air pressure fluctuations (acting on an instrument or on floor)
 - Sound (acting on instrument or on floor)

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External Sources

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- Traffic – Street, Subway, Rail
- Nearby Machinery – Can include items in nearby buildings
- Construction Activities
- Sound – Can include aircraft
- Ambient – Wind and waves

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A Major External Source

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Internal Sources

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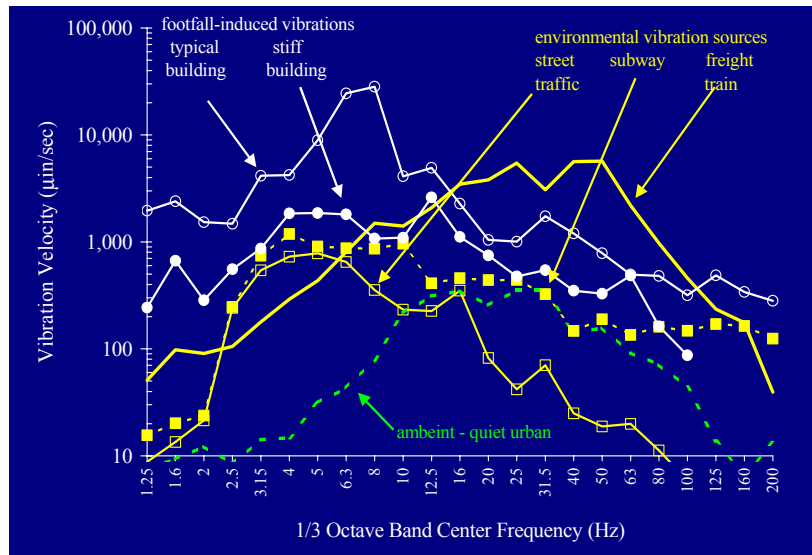
- People Walking, Footfalls
- Carts and dollies, fork lifts
- Doors opening and closing: Impacts and Pressure Changes
- Noise
- Maintenance and Installation Work
- Other Research or Production Equipment

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Typical Vibrations in Buildings

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Building Services Equipment

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- HVAC: Vibration, Noise, Pressure Fluctuations
- Exhaust: Fans in hoods or other service fans
- Electrical Eqpt: Emergency generators, transformers
- Pumps: Water, Vacuum
- Plumbing: Turbulence, Pulsations
- Ducting: Turbulence, Noise

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Vibration Measurements

Effects of Vibrations on Instruments

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Vibration Measurements

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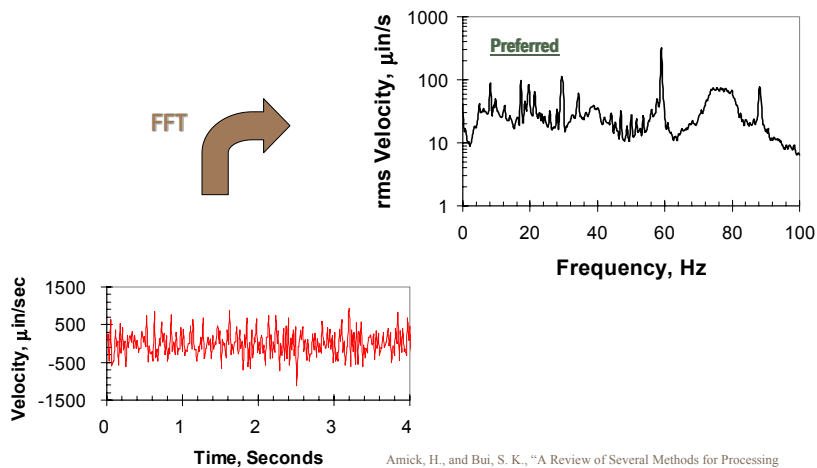
- **Measurement Process**
 - Instrumentation
 - Sensor – accelerometer or velocity sensor
 - Amplifier
 - Signal processing system
 - Attachment
 - Data capture
- **Data Reduction**
 - Download to computer
 - Process
 - Convert from format of signal processing to that needed for presentation
- **Data Presentation**
 - Purpose determines format
 - Documentation

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Time or Frequency Domain?

Hal Amick



Amick, H., and Bui, S. K., "A Review of Several Methods for Processing Vibration Data," *Proceedings of SPIE Conference on Vibration Control and Metrology*, pp. 253-264, San Jose, CA (November 1991)

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Relevant Spectrum Formats

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(i.e., appropriate for steady-state environments with significant random content)

- **Constant Bandwidth**
Fast Fourier Transform (FFT)
- **Proportional Bandwidth**
One-third octave band (bandwidth = $0.23f_c$)
- **Power Spectral Density (PSD)**
Acceleration² / Hz

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Preferences

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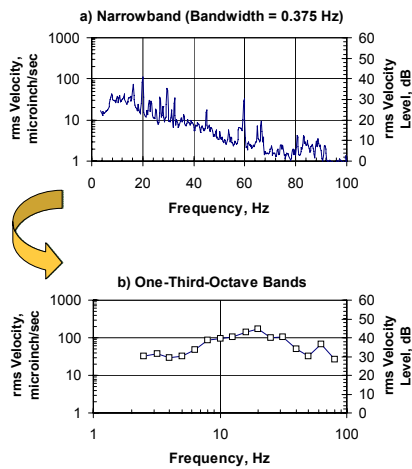
- **Frequency domain**
Majority of practitioners use FFT for diagnostics and 1/3 octave band for assessment
Also used: FFT alone, PSD
Response spectra *not* used (but being considered by ISO committee)
- **Energy Average statistics; RMS amplitude**
- **We use velocity**
(With spectra, the actual metric isn't critical as long as it is defined.)

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Example – “Typical” Site Vibration Measurements

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- Measure data “live”, obtaining spectrum directly with analyzer
- Measure in constant bandwidth (FFT)
- Convert to one-third octave bands

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Effects of Vibrations on Instruments

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- What do Vibrations do?
- Determining Vibration Sensitivity
 - Concept
 - Example – Optical Microscope
 - Manufacturers’ Specifications
- Generic Vibration Criteria
 - Manufacturers’ Specifications
 - Velocity “Bound”

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Typical Effects of Vibrations

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- **Optical Devices**
"Jiggle" or blurring of images – Impairment of visual observation
- **Electron Beam Devices**
Straight lines become wavy – Assessment errors, measurement errors
- **Probe-Type Devices**
Vibratory forces in sensor misinterpreted
- **Long-beam-path Devices**
Beams deflected, often causing energy loss or misalignment

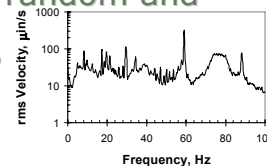
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Reasons for Vibration Sensitivity

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- **Vibrations (and sometimes sound) cause internal deformations**
Instrument is more responsive at its resonances
- **Floor vibrations are a mixture of random and single-frequency vibrations.**
What if excitation matches resonance?
- **Perform vibration sensitivity tests to develop criteria**
Identify resonances
Find "threshold" amplitude at which vibration's effects become a problem

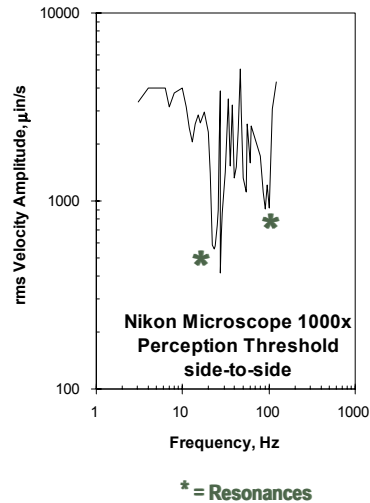


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Example – Nikon Microscope

- Shake microscope base at a fixed frequency
- Increase amplitude of motion until effect of vibration becomes visible
- Plot
- Repeat at new frequency
- Dips in curve associated with internal resonances



Amick, H., and Bui, S. K., "A Review of Several Methods for Processing Vibration Data," *Proceedings of SPIE Conference on Vibration Control and Metrology*, pp. 253-264, San Jose, CA (November 1991)

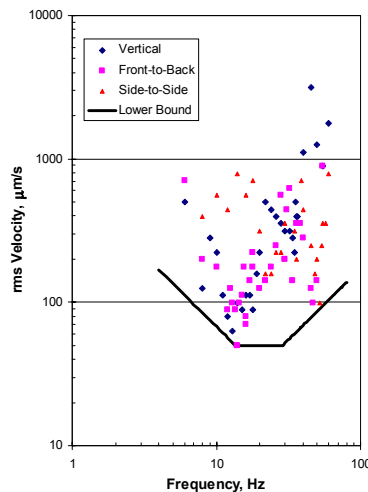
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Example – Nikon Microscope – 2

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- Perform test in three directions
- Plot points representing "threshold of perception"
- "Fit" appropriate lower-bound curves
 - Shown is lower bound of ...
 - \ - Constant Acceleration
 - _ - Constant Velocity
 - / - Constant Displacement
- Note what happens at lower frequencies



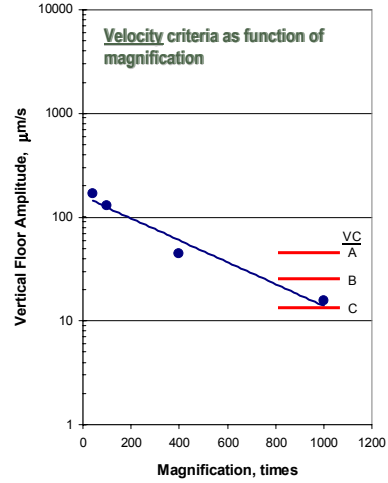
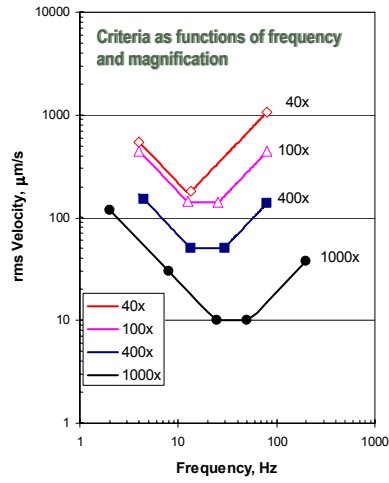
Hal Amick & Michael Stead, "Vibration Sensitivity of a Laboratory Bench Microscope," Presented at the First Pan-American/Iberian Meeting on Acoustics; 144th Meeting of the Acoustical Society of America, 2-6 December 2002, Cancun, Mexico

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Example – Nikon Microscope – 3

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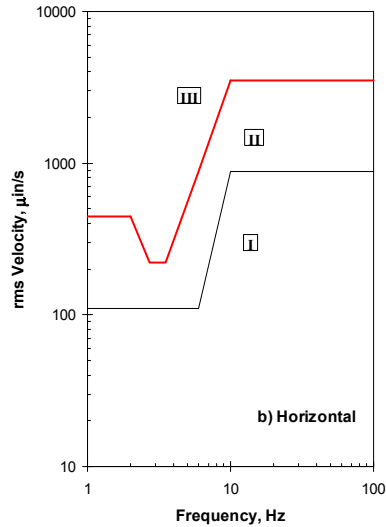
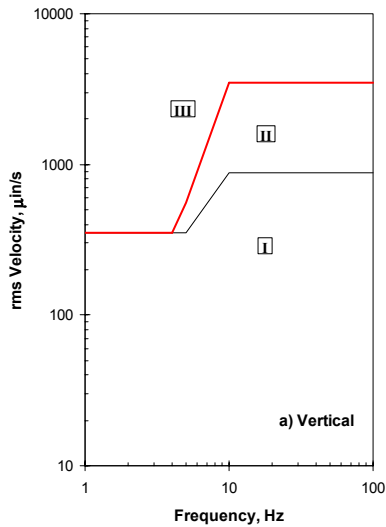
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Typical Manufacturer's Spec (TEM)

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One Popular Family of "Generic" Vibration Criteria

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1/3 O.B. Amplitude, $\mu\text{m/s}$ ($\mu\text{in/s}$)	Old BBN designation	IEST designation	ASHRAE designation	Typical Application*
100 (4000)			Curve F	Surgical suites
50 (2000)	BBN-A	VC-A	Curve E	"Generic" lab
25 (1000)	BBN-B	VC-B	Curve D	Non-Photo Semiconductor
12.5 (500)	BBN-C	VC-C	Curve C	
6.3 (250)	BBN-D	VC-D	Curve B	Semiconductor Photolithography
3.1 (125)	BBN-E	VC-E	Curve A	Nanotechnology

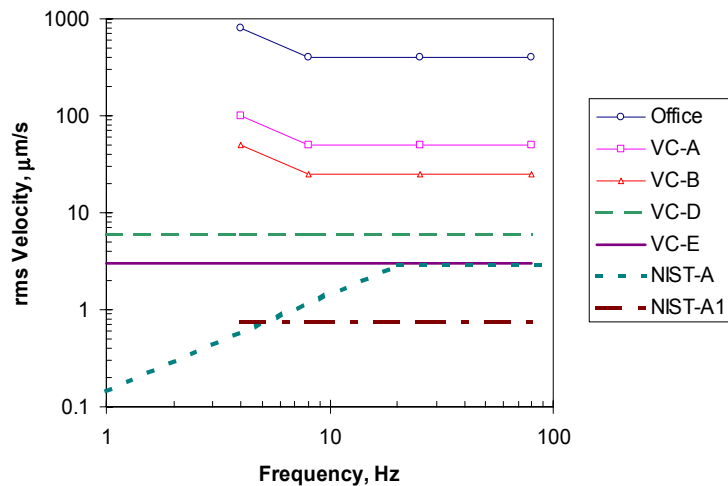
* See references cited at end
for detailed recommendations

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Compare Relevant Generic Vibration Criteria

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Summary

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- **Vibration Measurements**
Equipment and data processing
Typical data
- **Determining Vibration Sensitivity**
Example: Microscope
Example of good manufacturer's specification
- **Generic Vibration Criteria**
Original "BBN" criteria by Ungar and Gordon
Modification proposed by Ungar et al
Criteria from NIST AML project
- **Compared Generic Criteria with some Manufacturers' Specs**

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