Understanding and meeting vibration specifications with piezoelectric accelerometers

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ABSTRACT

Vibration specifications vary across industries and may include limits on acceleration, velocity, displacement, and/or dynamic stiffness. This paper outlines how piezoelectric accelerometers can be used to evaluate these criteria, particularly in precision environments. It also addresses the growing need to assess multi-axis vibration and foundation dynamic stiffnesses. We provide guidance on sensor selection and measurement strategies to meet stringent standards such as VC-G and NIST-A.

1. INTRODUCTION

There are many types of vibration specifications. High-value equipment must survive dynamic loads during operation and while being transported. Space equipment must endure extreme loads during launch. Other components have upper vibration limits that they must be able to endure, either for short periods or over many years. Modern precision manufacturing machines, such as photolithography systems, have very low allowable vibration requirements to minimize manufacturing errors. There are even allowable vibration limits for humans working with heavy machinery.

Acoustic noise limits are simple: sound measured with microphones cannot exceed certain levels. In contrast, vibration specifications are often applied in multiple directions - one vertical and two horizontal axes. In some cases, allowable fluctuating rotations in all three directions are also specified. Additionally, vibration specifications may define limits in terms of fluctuating displacements, velocities, or accelerations.

The wide variety of vibration specifications can make them difficult to interpret. Fortunately, simple accelerometer data can be used to evaluate any vibration specification, provided the appropriate sensor types are chosen. In this paper we explain several common vibration specifications and how to select the appropriate instrumentation and processing methods to evaluate them for your application.

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2. TYPICAL VIBRATION SPECIFICATIONS

Figure 1 shows a typical upper-bound acceleration spectrum for a space launch vehicle [1]. Engineers use curves like these to design components and equipment that can withstand the expected launch environments. The components are mounted to large shakers and tested over various periods of time to ensure both short-term and long-term survivability. This particular specification applies to the vertical direction (there are others for the two in-plane directions). There are two spectral curves—one for the initial stage of the launch (the "hold down" period) and another for the launch itself. The levels are power spectral densities (signal power within a frequency band divided by the bandwidth), and the units are in g. It is important to understand the specification format so you can properly compare your measurements to the specifications.

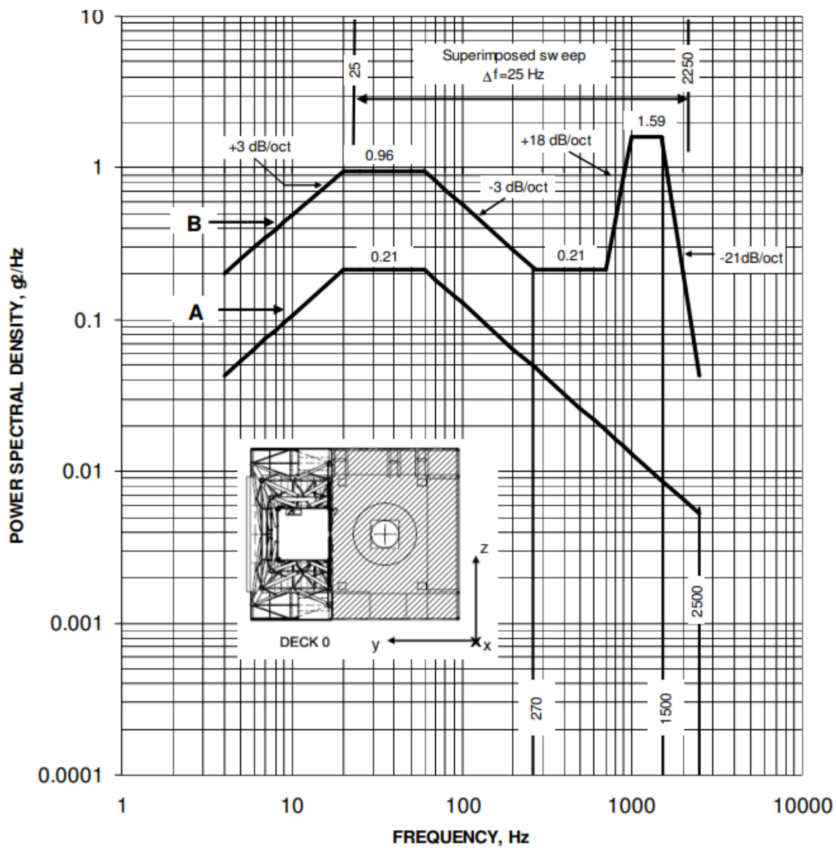

Figure 1: Typical space vehicle vibration upper bound for x direction from [1].

Figure 2 shows allowable vibration velocity (sometimes called particle velocity) levels for medium and large machines, taken from ISO 20816-3 [2]. Here, the levels are provided not in spectra, but in peak and rms levels evaluated over time. Different levels are specified for machines which are rigidly mounted to a floor and for those isolated with a flexible mounting system. Figure 3 shows another set of velocity levels, in this case used by engineers to assess potential vibration within buildings caused by nearby transportation sources [3]. Estimated source strengths are combined with ground attenuation models to compute levels within buildings in terms of VdB, which is RMS vibration velocity normalized by a reference:

$$L_v(VdB) = 20 \times log_{10}\left(\frac{v_{RMS}}{v_{ref}}\right) \qquad (1)$$

Be aware that the velocity references differ between regions: 1 μin/s is commonly used in the U.S., while the rest of the world usually uses 1-5 x 10^{-8} m/s. *Always confirm which reference value a dB specification is using*. Figure 3 also includes an example of how to determine both Peak Particle Velocity (PPV) and RMS velocity from a measured time history.

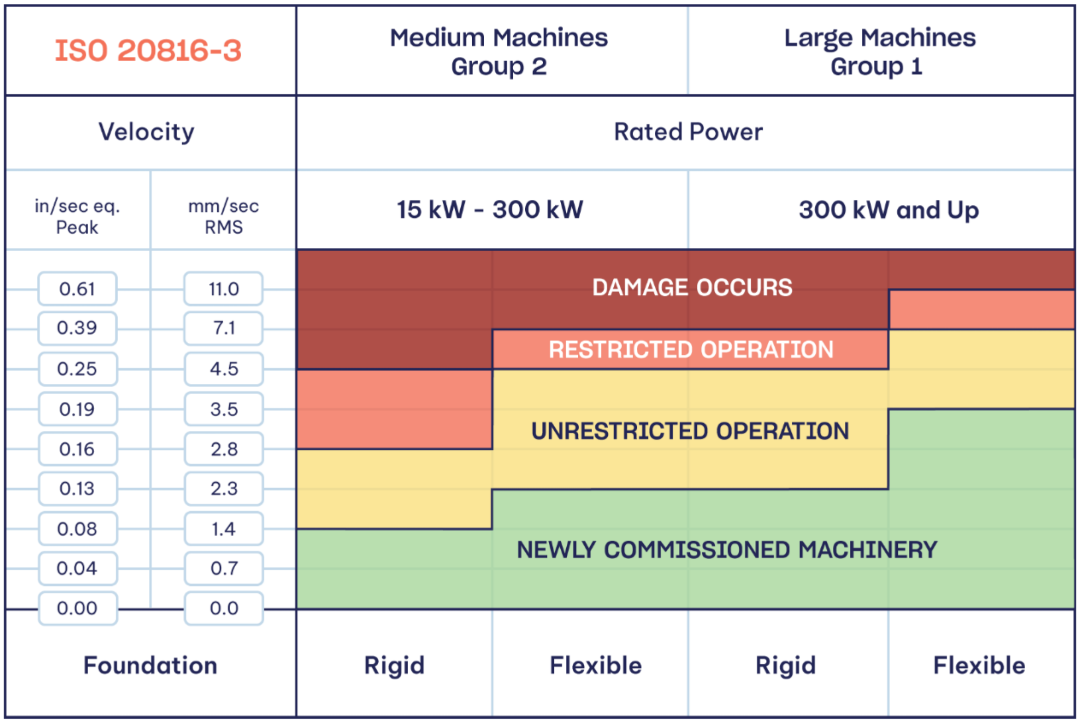

Figure 2: Allowable vibration velocity levels for machinery [2].

Occasionally, vibration limits are specified as displacements, usually for cases where gaps between components are small and intermittent contact must be avoided. Several engineering communities have published plots like the one in Figure 4, which illustrates the frequency dependence between displacement, velocity, and acceleration. Note the frequency and amplitude axes are both on logarithmic scales. The velocity curves are flat, with acceleration having positive slope and displacement negative slope. The plot simply shows the well-known frequency dependencies:

$$i\omega d(\omega) = v(\omega) = \frac{a(\omega)}{i\omega} \tag{2}$$

It was this frequency dependence that led to much of the community switching from acceleration specifications to velocity-based ones. Eric Ungar and Colin Gordon originally proposed simpler frequency-independent Vibration Criteria (VC) curves based on velocities after observing that manufacturer allowable acceleration specifications for electron microscopes (see Figure 4 from [4]) mostly followed a simple frequency dependence. Over time, their curves were adopted by much of the vibration measurement community. You can read about the history of the VC curve evolution in [5] and [6]. In particular [6] summarizes a long-standing debate over whether the curves refer to RMS, peak, or some other quantity. The most recent adoption of the VC criteria by IEST [7] in 2024 includes guidance on this point, based on whether peak vibrations are expected to be intermittent or mostly constant.

Land Use Category	GBV Impact Levels (VdB re 1 micro-inch /sec)		
	Frequent Events	Occasional Events	Infrequent Events
Category 1: Buildings where vibration would interfere with interior operations.	65 VdB*	65 VdB*	65 VdB*
Category 2: Residences and buildings where people normally sleep.	72 VdB	75 VdB	80 VdB
Category 3: Institutional land uses with primarily daytime use.	75 VdB	78 VdB	83 VdB

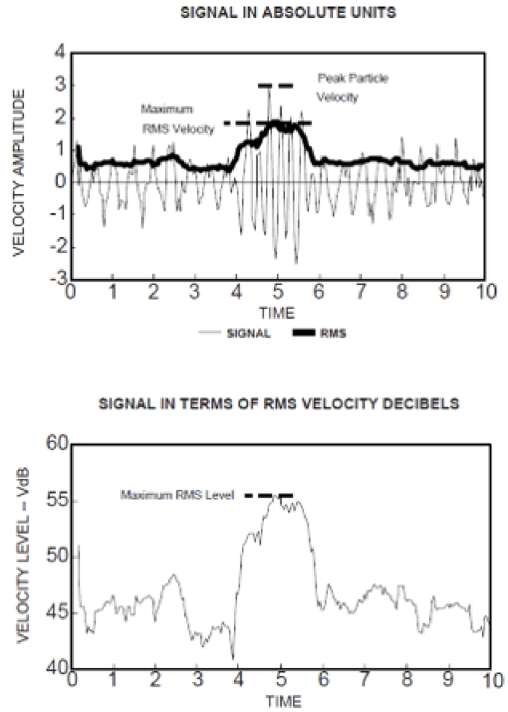

Figure 3: Allowable ground-borne vibration velocity levels for transportation sources [3].

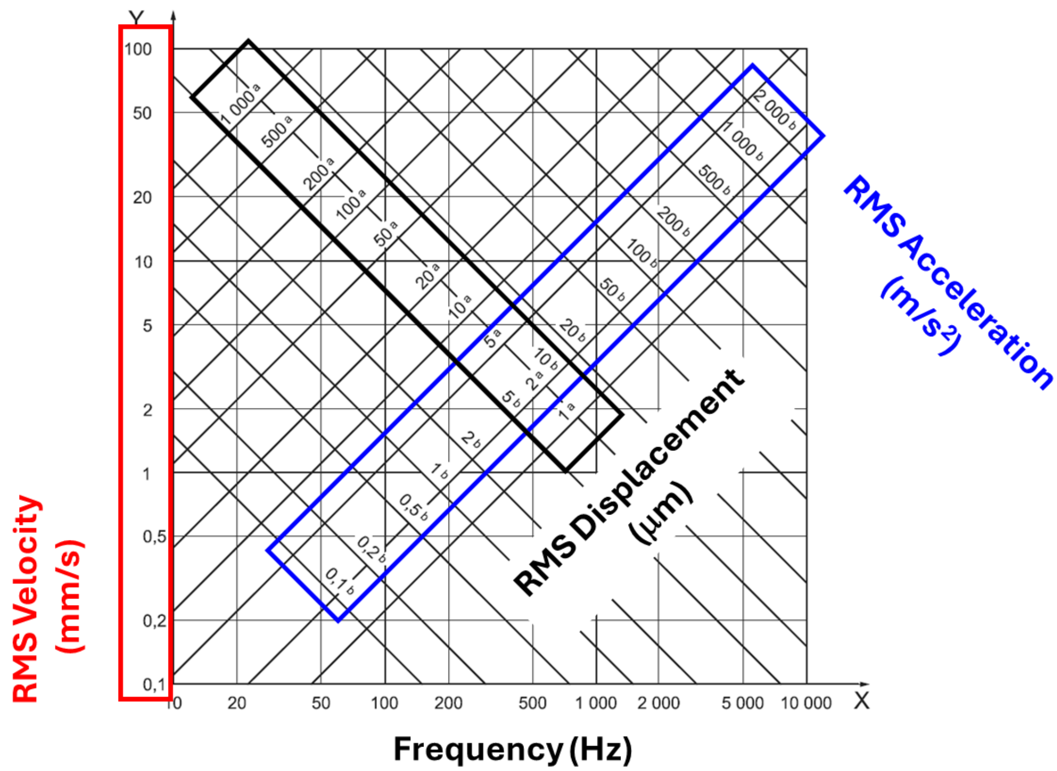

Figure 4: Vibration in terms of displacement, velocity, and acceleration.

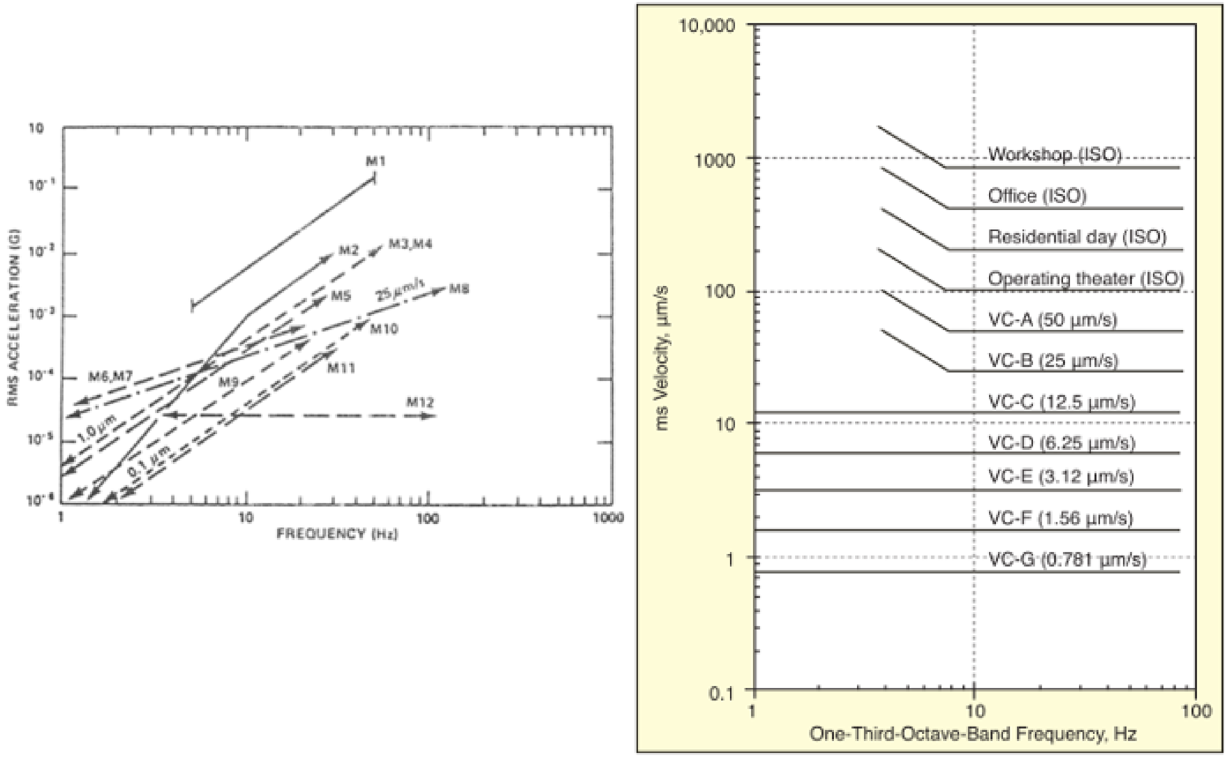

Figure 5: Left: Early vibration specification in g's for 12 electron microscopes from [4]; Right: Vibration Criteria (VC) curves for velocities, including lower-level limits (VC-C through G) [5].

3. TYPICAL VIBRATION SOURCES AND TRANSMISSION

The specifications we've shown so far cover a wide range of applications and scenarios. This section focuses on vibrations in buildings that house sensitive equipment, such as scientific measurement systems and semiconductor manufacturing facilities. The requirements in semiconductor manufacturing facilities are particularly stringent; see [8, 9] for more detail.

Major sources of vibration in buildings include trains, large vehicles (such as trucks), nearby equipment and machinery (including HVAC systems), and in certain locations, seismic events. Another major contributor is large-scale construction near a facility, particularly activities like pile driving. Specifications like the VC curves are intended to ensure sensitive equipment can operate properly in the presence of any of these sources.

In some cases, engineers are asked to estimate whether a given building location will be compliant with a given VC curve. To do this, the engineer must estimate:

- the strength and frequency content of various sources,
- the expected attenuation of various source signals over the ground and into the building, and
- the effects of isolation mounting, if included.

During early design stages, bounding conditions are used to estimate a worst-case vibration level. If those levels violate the desired VC curve (or another relevant specification) more detailed assessments are required. These may include transfer function measurements between intended equipment locations and the key source points or intermediate locations along a transfer path. The source strengths can be estimated using ground-borne vibration measurements and combined with the transfer functions to produce detailed estimates of expected vibration levels. These estimates are often used to select optimal machine locations and to decide whether expensive isolation mounting is required.

Figure 6 shows typical time histories of horizontal ground vibration near a large seismic event, presented in terms of displacement, velocity, and acceleration. Although this is an unusually strong event, the character is typical of strong transients lasting a few seconds.

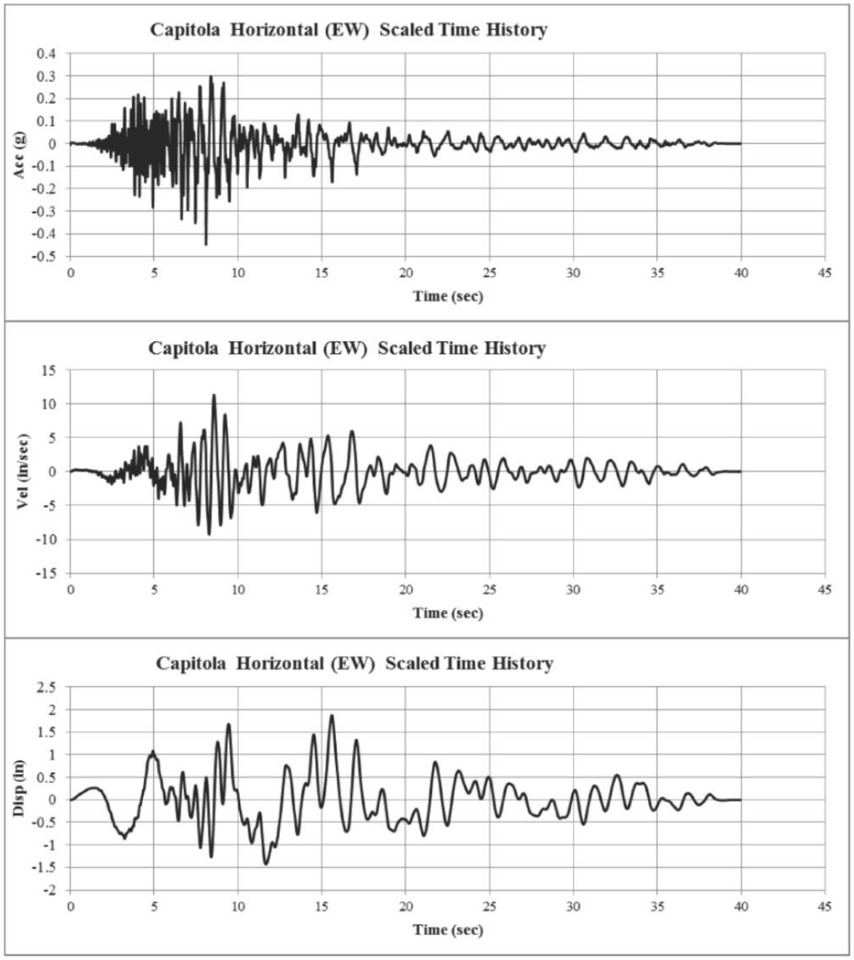

Figure 6: Typical seismic event vibration acceleration (top), velocity (middle), and displacement (bottom).

Table 1, reproduced from [10], summarizes typical vibration levels from construction events, including heavy truck transport. Figure 7, also from [10], shows measured vibration levels induced by several trains at various distances from the tracks. The wide variability is due not only to the different train types but, more importantly, differences in ground-borne transmission.

The earth beneath our feet is highly variable, composed of several layers of dirt of different compositions—and therefore different propagating wave speeds and, at times, considerable attenuation. These layers ultimately rest on solid bedrock, which supports very fast propagating wave speeds and little attenuation. The ground differences between locations lead to significant differences between propagation attenuation behavior which must be accounted for when estimating vibration levels in buildings. Figure 8 compares ground vibration levels over distance from the same train in three different countries (France, Italy, and Sweden). We have added the common 65 VdB requirement shown in Figure 3, which corresponds to about VC-A in Figure 5. The distance necessary to meet the requirement varies from 150 ft in France to 250 ft in Italy. A building would need to be more than 500 ft from tracks in Sweden to meet the requirement.

Table 1: Typical vibration source levels from construction equipment and truck transportation from [10].

Table 10-4 Vibration Source Levels for Construction Equipment
(From measured data.[10,11,12,13])

Equipment		PPV at 25 ft (in/sec)	Approximate L_v† at 25 ft
Pile Driver (impact)	upper range	1.518	112
	typical	0.644	104
Pile Driver (vibratory)	upper range	0.734	105
	typical	0.170	93
Clam shovel drop (slurry wall)		0.202	94
Hydromill (slurry wall)	in soil	0.008	66
	in rock	0.017	75
Large bulldozer		0.089	87
Caisson drilling		0.089	87
Loaded trucks		0.076	86
Jackhammer		0.035	79
Small bulldozer		0.003	58

† RMS velocity in decibels (VdB) re 1 μinch/second

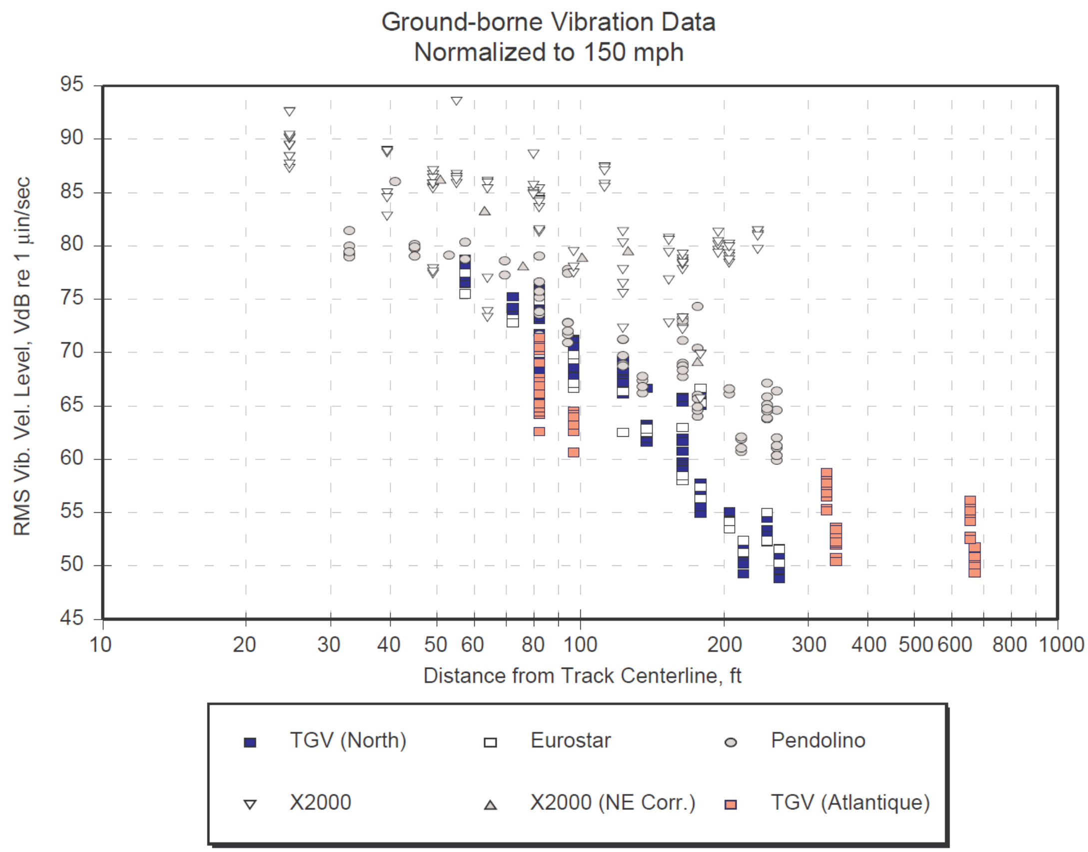

Figure 7: Train vibration source strengths at different distances from track [10].

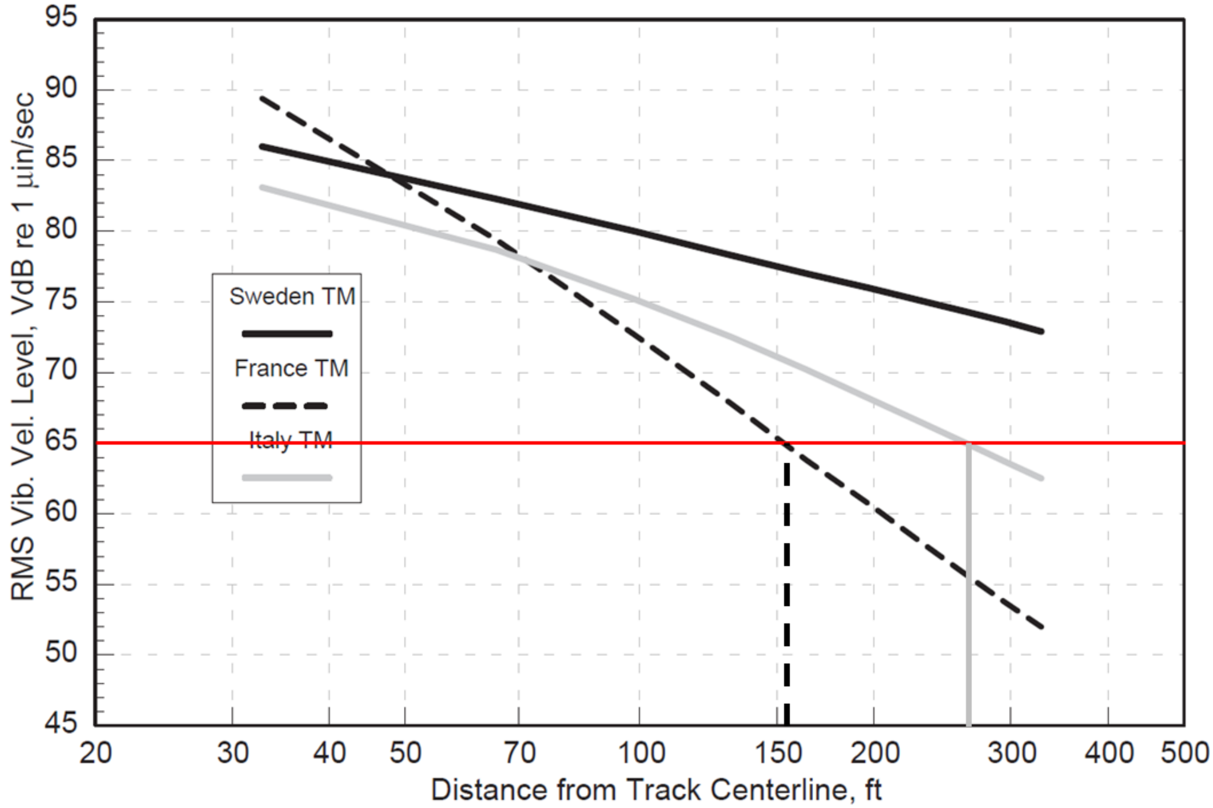

Figure 8: Train vibration source strengths at different distances from track [10]. 65 VdB limit highlighted in red with minimum distance requirements shown for the Italy and France locations.

4. ACCELEROMETER SELECTION

The VC-A criterion is far too lenient for highly sensitive manufacturing machines. To evaluate compliance with more stringent vibration requirements a high-sensitivity accelerometer is required [8]. A standard model such as the PCB 352C03 can measure below VC-B levels, as shown in Figure 9. In that figure, the accelerometer noise floor (from its specification sheet—see [11] for guidance on noise floors and related limits) is plotted in terms of RMS velocity in one-third octave bands (consistent with the VC curve format).

The lowest standard VC curve is VC-G, which specifies a flat 0.781 µm/s velocity limit across all frequencies. An even more stringent vibration requirement, commonly referred to as NIST-A, was used to design the US National Institute of Standards (NIST) Advanced Measurement Laboratory. The NIST-A curve applies a constant displacement requirement of 25 nm below 20 Hz. Remember the frequency dependence relations we discussed earlier? The constant displacement requirement causes the low-frequency NIST-A velocity curve to slope downward with decreasing frequency.

Figure 10 compares the noise floors of the ultra-high-sensitivity PCB 393B31 and the newer PCB 393C31 (both with sensitivities of 10 V/g) against VC-G and NIST-A. You can use these types of accelerometers to evaluate VC-G compliance across the full frequency range, and NIST-A compliance at frequencies down to approximately 0.5 Hz.

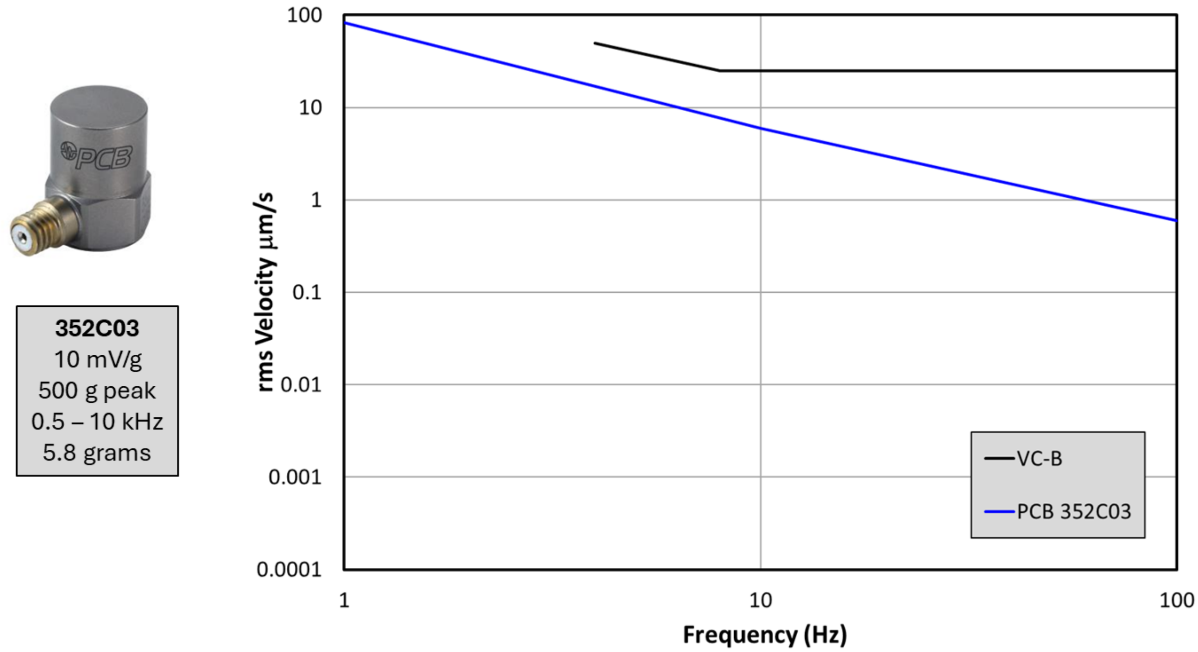

Figure 9: PCB 352C03 noise floor vs. VC-B vibration limits.

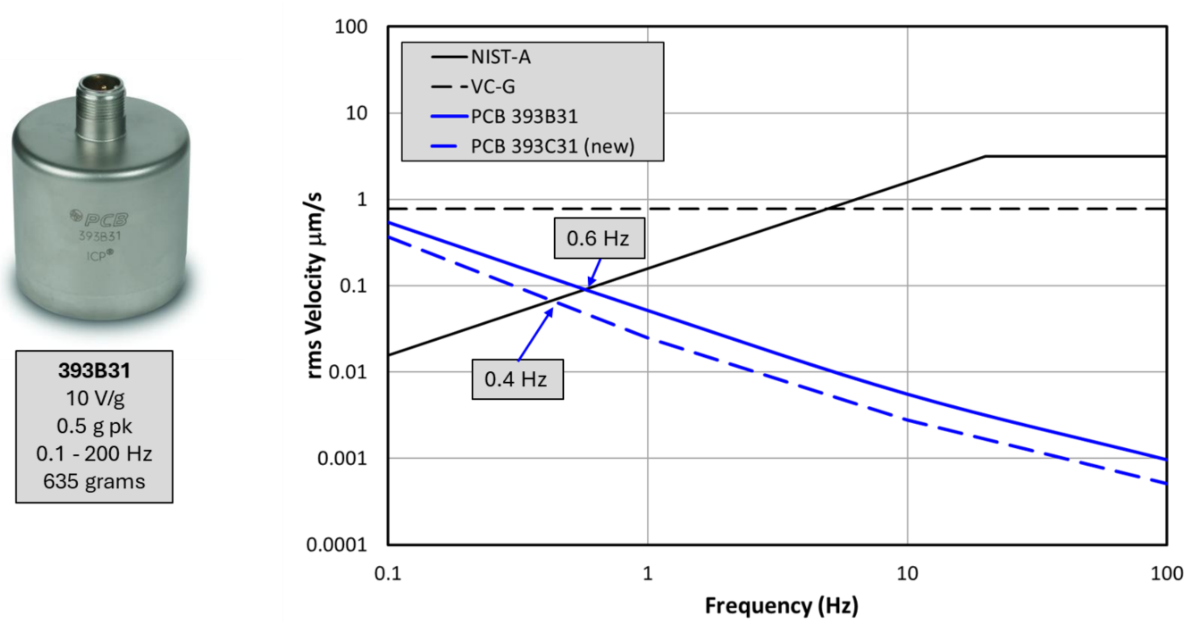

Figure 10: PCB single-axis seismic accelerometer noise floors vs. VC-G and NIST-A limits.

5. MULTI-AXIS SPECIFICATIONS AND ACCELEROMETERS

A growing trend in the semiconductor community is for equipment manufacturers to specify minimum allowable dynamic stiffnesses at building foundation locations [12]. Newer photolithography machines generate dynamic positioning forces to control the reticle and stage. These forces, combined with the allowable displacements, are used to specify minimum dynamic stiffnesses. Dynamic stiffness is the inverse of the compliance:

$$\frac{F}{d}(\omega) = \frac{1}{\frac{d}{F}(\omega)} \qquad (3)$$

This quantity can be measured using floor- or foundation-mounted accelerometers and by applying known input forces with either large shakers or instrumented force hammers.

A typical dynamic stiffness specification is shown in Table 2. Levels are specified in all three directions and also for rotational stiffnesses (dynamic moment divided by angular rotation). Evaluating a foundation's multi degree of freedom stiffness compliance requires more than one accelerometer. Tri-axial accelerometers, such as the new seismic PCB 354A12, provide the simplest means of measuring the various foundation dynamic stiffnesses. By placing three tri-axial accelerometers with known separations along the two horizontal axes, engineers can compute all the transfer functions needed to compare to the specifications.

A cautionary note: many engineers have used single-axis accelerometers mounted to cubic blocks of metal to simulate tri-axial measurements. If done with care, this methodology is acceptable. However, if the accelerometers are not mounted properly (see [13] for best practices), or their relative directions are not perfectly orthogonal (each 90 degrees from the other following a right-hand rule), it's all too easy to bias your measurements significantly, particularly when estimating rotational stiffnesses.

One key performance specification for tri-axial accelerometers is cross-talk, or the maximum amount of signal that can occur in an off-axis direction to an applied force. For example, how much false vibration do you measure in the Y direction when driving a system in the X direction? Every PCB accelerometer spec sheet lists transverse sensitivity, which quantifies this effect. Tri-axial accelerometers are carefully assembled to minimize cross-talk.

Table 2: Typical foundation minimum dynamic stiffness requirements for Semiconductor equipment.

Direction	Main Structure	Mechatronic Components
Z	2×10^8 N/m	5×10^8 N/m
X,Y	3×10^8 N/m	6×10^8 N/m
Rz	3×10^8 Nm/rad	5×10^8 Nm/rad
Rx, Ry	4×10^8 Nm/rad	6×10^8 Nm/rad

6. SUMMARY

Meeting vibration specifications is more challenging than meeting acoustic ones. Whereas acoustic requirements typically just define maximum allowable pressure levels, vibration specifications may define limits on displacement, velocity, acceleration and, more recently, dynamic stiffness (force per unit displacement). These specifications often apply in three directions and sometimes include rotations.

Vibration specifications are also written differently across various communities, which makes it difficult for a test engineer to ensure compliance with all of them. Perhaps the most popular specifications in the precision manufacturing community are the Vibration Criteria (VC) curves, which define velocity vibration limits that remain mostly constant across frequencies.

Most seismic high-sensitivity accelerometers should measure signals below the VC-G curve. Ultra-high-sensitivity accelerometers (10 V/g) are required to measure vibrations below the more stringent NIST-A standard. When dynamic stiffnesses are specified in multiple degrees of freedom, tri-axial accelerometers are an accurate and convenient way to capture the full set of required measurements

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