

Review of Generic and Manufacturer Design Criteria for Vibration-Sensitive Equipment

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ABSTRACT

The instrumentation employed today in fields such as nanotechnology require equipment such as scanning electron microscopes, lithography steppers, and nanoindenters, whose performance depends on micron-level precision. For example, in a scanning electron microscope, the electron beam used to scan the object must not be interrupted or misguided if an accurate image is to be produced. Even the slightest vibration transferred from the supporting structure can disturb the equipment's performance. The structural engineer must design a structure to house this equipment while meeting these strict vibration limits. Because the structural design usually precedes the selection of equipment, the engineer is often utilizes generic design criteria to design the supporting structure. The generic design criteria and manufacturer-specified design criteria are often in unfamiliar terms. This study examines and interprets several manufacturer-specified design specifications and how they relate to the industry's current generic design criteria. Terminology, metrics, and conversion methods are explained so that the manufacturer-specified criteria can be properly interpreted. Recommendations are made for specifying complete design criteria and for the cautious use of the generic design criteria.

INTRODUCTION

Technological advances in both manufacturing and research often require or result from an increase in precision. This increase in precision imparts new tolerance levels on such external factors including vibration because precision at this scale can be disturbed by even the slightest movement or vibration. For this reason, the structural system supporting such equipment must be designed to preclude vibration that interferes with the equipment's proper operation.

Most manufacturers of this type of precision equipment have performed vibration analysis on the equipment and are providing some level of vibration specifications with their equipment. However, the equipment and therefore the vibration specifications are rarely selected and positioned prior to the design and construction of the structure. New advances in methods and equipment can occur in the time the structure is designed and new advances will almost certainly occur throughout the life of the structure. For this reason, generic design criteria were developed in the early 1980's for cases when the specific equipment criterion was not yet available and this generic design criteria have since been revised slightly. These generic design criteria and how they relate to the more accurate equipment specifications is the subject of this review.

This paper begins with an overview of vibration sensitive equipment and is followed by a short history of the development of the generic vibration design criteria curves. For this study, vibration specifications were solicited from several manufacturers and analyzed. The individual vibration specifications were then compared to the generic criteria to evaluate the effectiveness of such generic criteria in representing actual performance criteria. During this review, several discrepancies arose in how the individual vibration specifications were presented including the meter, the amplitude units, and differences between narrow and 1/3 octave bands analysis results. These discrepancies, as well as the comparison with the generic criteria, are presented here along with several reflections on the current state of knowledge regarding sensitive equipment.

BACKGROUND

Vibration Sensitive Equipment

Precision equipment that can be affected by vibration is utilized in many industries including fabrication or manufacturing of microchips and other electronic equipment, research involving particle or laser beams for magnification or measurement, and medical equipment such as a magnetic resonance imaging (MRI) machine that requires precision in the location and straightness of the magnetic lines for accurate imaging. The precision that is required by these types of equipment is in the range of micrometers (10^{-6} m) to picometers (10^{-12} m). The slightest vibration or movement can cause the equipment to go out of its tolerance range and yield the resulting information unusable. This could prove to be a financially costly disruption, in terms of a manufacturing or fabrication plant, or a time costly disruption, in terms of research. If the out-of-tolerance movement is not identified, it could result in inaccurate images or measurements.

Understanding the vibration criteria or specification requires a general understanding of the proper operation of the equipment as well as its position in the overall production or experimental processes. The design engineer must be aware of the vibration criteria for the different types of equipment that are expected in the structure in both the current state and future expectations, as well as the possible sources of vibration.

Generic Vibration Criteria

Because the equipment and associated vibration criteria are not always selected or known prior to the design and construction of a structure, generic guidelines were developed to aid in the design process. The guidelines were to provide an upper bound on the level of vibrational velocity for different classifications of equipment based upon the processes that are essential for proper operation of the equipment. These guidelines are known as the Vibration Criterion (VC) curves and are shown in Figure 1. These curves were originally developed in the early 1980's by Eric Ungar and Colin Gordon while working at Bolt Beranek and Newman (BBN) and originally known as the BBN criteria. The vibration curves were developed with the semiconductor industry in mind but their use has been more widespread. The original criteria included four levels of vibration: VC-A through VC-D where VC-A was the most lenient and VC-D was the most stringent criteria. Since the original development, vibration levels VC-E through VC-G have been introduced as technology advanced and the sensitivity of equipment increased. The criterion associated with VC-F and VC-G is not intended for design purposes, but rather as a classification system. In 2002, the downward slope at the lower frequencies from the five lowest vibration levels, VC-C to VC-G, was removed to account for the increased sensitivity of modern equipment at lower frequencies.

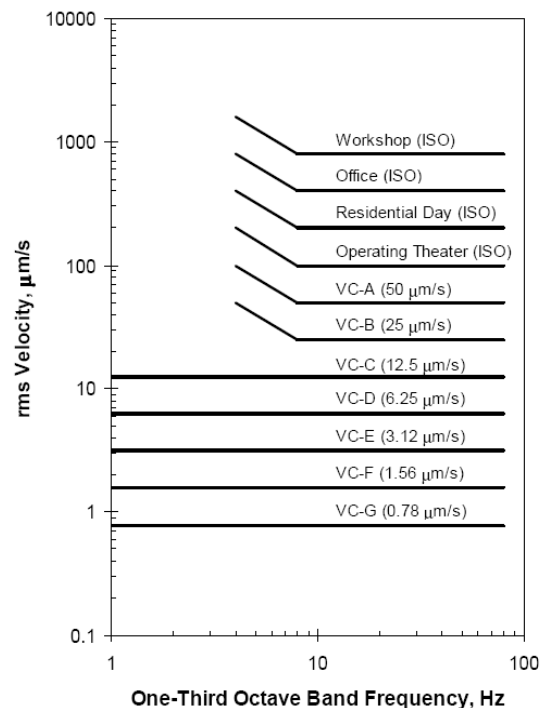


Figure 1: Generic vibration criterion (VC) curves for vibration-sensitive equipment and ISO guidelines for vibration in buildings (from Amick 2005)

INDIVIDUAL MANUFACTURER SPECIFICATIONS

Manufacturers of equipment have long recognized the sensitivity of their equipment but have not always had the facilities or expertise to perform the testing required for the development of an accurate and appropriate specification. As technology has advanced and the equipment has become increasingly more sensitive to vibration, it appears that more manufacturers are able to perform appropriate testing resulting in more detailed specifications. However, there is still a large variability in the information provided in manufacturer's specifications and there are some common discrepancies and inconsistencies present that have been identified through both a literature review and through an examination of vibration specifications from several equipment manufacturers. These common issues are briefly identified here and will be discussed in more detail in the description of each of the example specifications.

One of the first and most obvious issues that a manufacturer specification can include is to claim that the environment must be ‘vibration-free’ in order to be suitable for accurate operation of the equipment. This statement is flawed because a ‘vibration-free’ environment does not exist, regardless of the structural design of the building. All structures, even a slab-on-grade, are inevitably prone to some vibration, albeit at a very low level. A similar issue arises when the specifications are based purely on a constant displacement criterion yielding an extremely low level of allowable acceleration at low frequencies. These limits on low frequency vibration are unrealistic and unattainable, yet have been included in manufacturer’s specifications.

If vibration testing is performed, several issues can arise with how the specifications are presented. The specifications can be indicated in terms of acceleration, velocity, or displacement but specifications in acceleration or displacement terms are uncommon. Guidance for structural design is based on velocity in several widely-recognized publications and the generic vibration curves are also presented in terms of velocity. The magnitude of the vibration can also be presented in terms of peak, peak-to-peak, or RMS amplitudes. Failure to identify which amplitude measurement method is used can render the specifications useless or applied improperly.

Another possible issue is the frequency range for which vibration limits are provided. If this frequency range is a single frequency or a narrow range, it is impossible to assess the acceptability of a structure for frequencies outside of this range. If the frequency range is too broad, it can be difficult to accommodate the excitation limits at all of the frequencies prescribed. The results of the vibration testing can be presented in two ways: one-third octave bands of frequency or by specifying the measurement bandwidth. One-third octave band analysis was originally developed from the acoustics industry and is the presentation method of the generic vibration curves. Most guidance presents the allowable spectrum in one-third octave bands but some manufacturers have also presented their test results in a narrowband analysis.

The vibration specifications should also include some reference to the length of time that a piece of equipment must remain in operation uninterrupted. If an isolated vibration greater than the allowable limit occurs once within a 24-hour period, does this serviceability failure require the replication of a 5-minute experiment or a 24-hour experiment? The significance of the time loss and expense associated with each vibration incident are important considerations when identifying the stringency of the vibration design criteria. A tradeoff between the original design and construction costs of a structure designed to a more stringent vibration criteria must be weighed against the sum of the time and expense loss associated with a structure designed to a less stringent vibration criteria.

To forego extensive vibration testing, manufacturers may also elect to refer only to the existing generic criteria. It is believed that these generic criteria are conservative and would be adequate. This study examines the specification of several manufacturers for comparison with the generic vibration criteria to examine this assumption as well as the other possible issues with specifications that were previously discussed.

SAMPLED MANUFACTURER SPECIFICATIONS

Vibration specifications were collected from several manufacturers for eight pieces of equipment and the specifications were examined for completeness, interpretation difficulties, and comparison with generic criteria. The specifications in this study are only identified by a variable denoting each manufacturer. The equipment types for which vibration specifications were collected are listed in Table 1. Each type of equipment is labeled with the VC criteria generally associated with each type of equipment from design standards for sensitive equipment (Murray *et. al* 1997, Ungar *et. al* 1990).

Table 1: Sampled equipment, type, and associated VC criteria

Manuf./Equip. Designation	Equipment Type	Associated VC Criteria
A1	SEM	VC-D
A2	SEM	VC-D
B1	Scanning Nanoindenter	<i>not listed</i>
C1	Stepper	VC-B or VC-C
D1	Stepper	VC-B or VC-C
D2	Scanner	VC-B or VC-C
E1	Lithography Platform	VC-B or VC-C
F1	TEM	VC-D

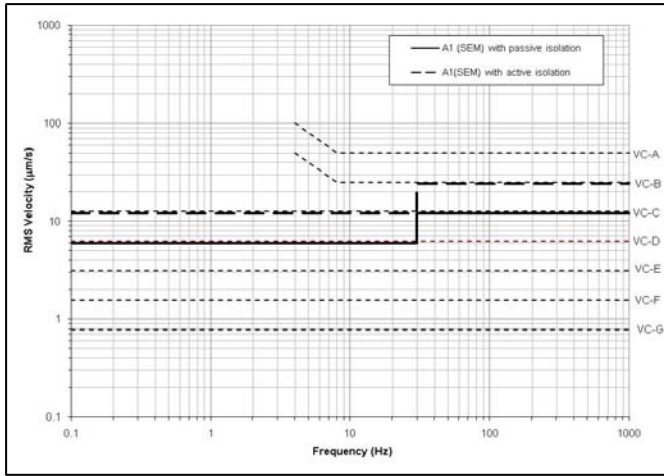


Figure 2: Manufacturer-provided vibration specification for A1 (SEM)

systems are utilized. Active isolation involves the sensing of vibration by internal sensors and utilizing the feedback from these sensors to control the vibration. The specifications are presented in RMS velocity units and are constant over two frequency ranges as shown in Figures 2 and 3.

The next specification from Manufacturer B is for a scanning nanoindenter that is not directly referenced in the generic VC criterion because of the relatively new nature of the equipment. Equipment using the methods of scanning nanoindentation and scanning probe microscopy utilize a probe to ‘feel’ a surface rather than ‘see’ a surface and provide methods for imaging and material characterization. Even the slightest vibration will affect the probe’s location and pressure resulting in erroneous results and require replication of the test. This particular nanoindenter is a

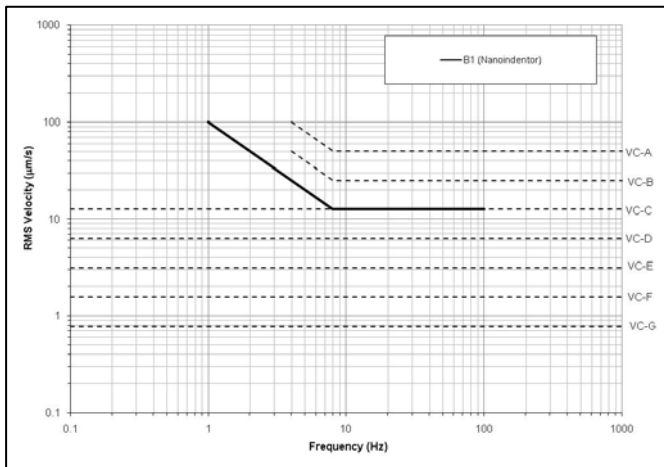


Figure 4: Manufacturer-provided vibration specification for B1 (Nanoindenter)

project the image onto the various layers that form the microchip that are later ‘etched’ with this pattern. The projected image is then ‘stepped’ and repeated in a grid-like pattern over the microchip surface. Any vibration will

The first two specifications collected from Manufacturer A are for scanning electron microscopes that would typically be associated with the VC-D generic criteria. A scanning electron microscope utilizes a beam of electrons to scan across a specimen to produce a magnified image. The precision with which the electron beam is directed and the straightness of the beam are critical for the production of an accurate image and are the reason for the vibration specifications. These particular SEM models are relatively small, compact, and have a lower cost. SEM A1 has a resolution of 3 nm while SEM A2 has a resolution of approximately 1 nm. With the relatively higher resolution available in SEM A2, it is expected that the vibration criterion is more stringent than for SEM A1. The manufacturer provided specifications that include different criteria for when active isolation systems are included and when only passive isolation

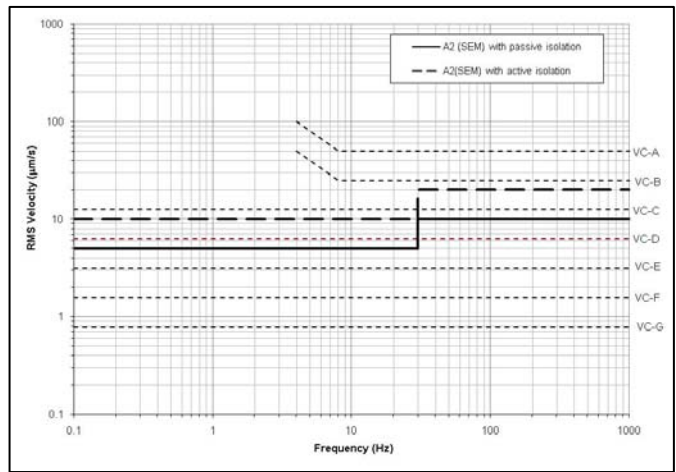


Figure 3: Manufacturer-provided vibration specification for A2 (SEM)

single, compact platform with a load resolution of 1 nN and a displacement resolution of 0.0004 nm. The specification is presented in RMS velocity units for the frequency range between 1 and 100 Hz and follows the VC-C generic criterion curve in this region. The specification is shown in Figure 4.

Manufacturer C provided specifications for a stepper/aligner used in the fabrication of integrated circuits or microchips. In the microchip manufacturing process, microlithography techniques are utilized to ‘etch’ a geometric pattern into the surface of a semiconductor material and the stepper or aligner locates the pattern on the chip. Photolithography techniques use light and a light-sensitive chemical to ‘etch’ the image into a material similar to the fundamental principles of photography. Lithography steppers such as this piece of equipment operate similar to a slide projector through which light passes to

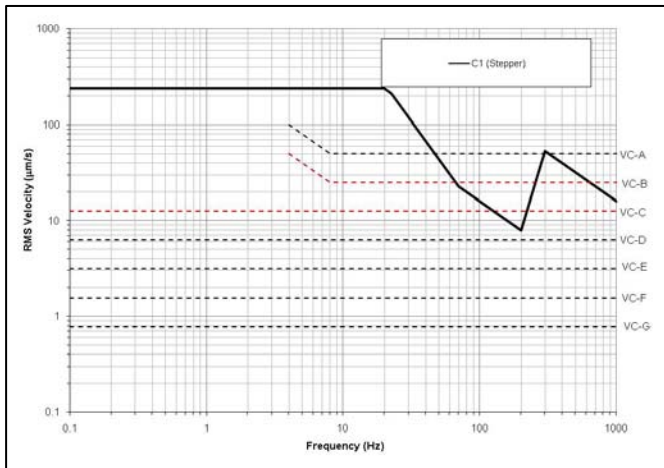


Figure 5: Converted manufacturer-provided vibration specification for C1 (Stepper/Aligner)

Manufacturer D also provided specifications for a stepper (D1) used in the semiconductor fabrication industry and would be considered in the range of VC-B or VC-C in the generic criteria. The manufacturer's specifications provide data for the frequency range of 1 to 100 Hz in 1/3 octave band increments. The data is presented in all three meters of acceleration, velocity, and displacement but does not mention the amplitude measure: RMS, peak, or peak-to-peak. The generic VC-D curve was presented on the same graph so the assumption is made that the data is also presented in RMS units. The velocity measure of the specification is shown in Figure 6 in the assumed RMS units. The vibration specification is also presented in narrow bands of 1 Hz as compared to the primary presentation method of 1/3 octave bands.

distort or move the projected image and etching process and will disturb the fine precision required on such small microchips. Vibration above the equipment's tolerance level will result in costly production losses. The resolution of this particular stepper is 0.25 micrometers and would be considered in the range of VC-B or VC-C criterion. The manufacturer's specification provides data for the frequency range from 1-1000 Hz in terms of the allowable acceleration of the floor structure. The specification failed to identify how the acceleration amplitude was considered: RMS, peak, or peak-to-peak. For comparison with the VC curves, this data was converted to RMS velocity units using the relationships discussed earlier. The resulting converted specification is shown in Figure 5.

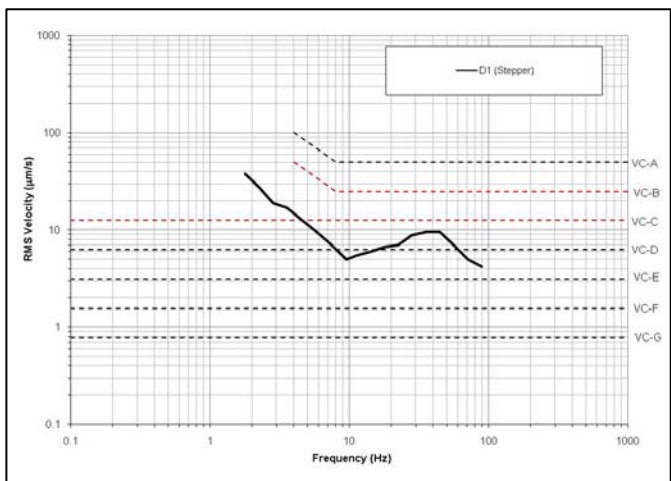


Figure 6: Converted manufacturer-provided vibration specification for D1 (Stepper)

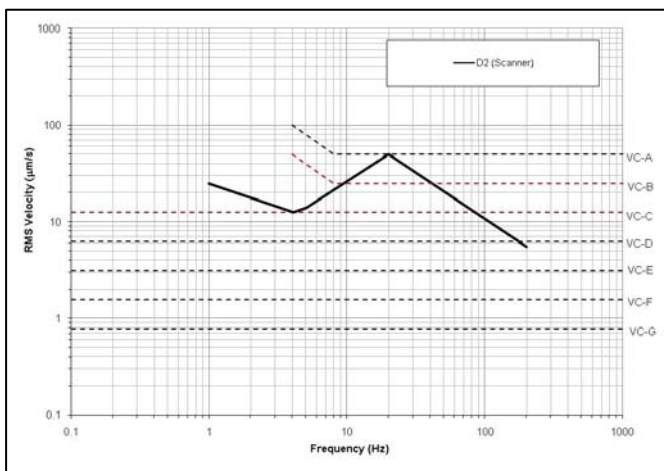


Figure 7: Converted manufacturer-provided vibration specification for D2 (Scanner)

productivity of the equipment. Similar to the individual stepper or scanner, this lithography platform would be considered in the range of VC-B or VC-C of the generic vibration curves. The manufacturer's specifications were provided for the frequency range of 1 to 100 Hz in terms of the power spectral density of acceleration of the floor structure. The manufacturer also provided the same specification in a tripartite format of the RMS vibration

Manufacturer D also provided specifications for another type of stepper, a scanner (D2). A scanner performs the same function but in a different way. In a scanner, both the projected image and the microchip are 'stepping' with respect to each other. The specifications were originally provided in terms of the power spectral density of the acceleration of the floor structure for each of the components of the scanner. The specifications were also alternately presented in a tripartite format which includes acceleration, velocity, and displacement on a single graph. The specifications were converted to RMS velocity units in 1/3 octave bands for comparison with the generic criteria as shown in Figure 7.

A vibration specification was provided by manufacturer E for a double-phase lithography platform that is similar to the stepper and scanner but increases the overall

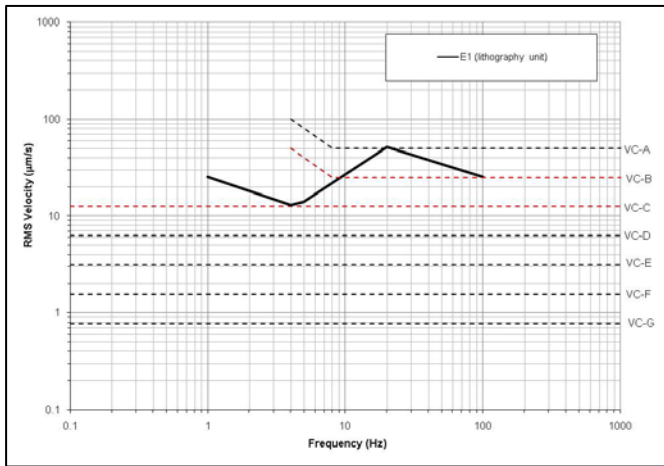


Figure 9: Converted manufacturer-provided vibration specification for E1 (Lithography platform)

provided in terms of the displacement amplitude over a frequency range of 0.3 – 1000 Hz. The specification was expressed in terms of the power spectral density and peak-to-peak measurements. The specification also provided guidance for converting the peak-to-peak amplitude values to RMS amplitude values. The converted specification is shown in Figure 9.

As described for each sampled piece of equipment, the meter used in development of the specification and the presentation method can vary by: the units of acceleration, velocity, or displacement; the amplitude measurement of RMS, peak, or peak-to-peak; or the frequency analysis method of 1/3 octave band or narrow band analysis. In order to compare the manufacturer specifications with the generic vibration guidance, conversion to RMS velocity units presented on 1/3 octave bands is necessary. The following computations were performed as necessary:

Conversion from acceleration to velocity:

$$v = a / (2 \pi f) \quad (1a)$$

where: v = velocity
a = acceleration
f = frequency (Hz)
d = displacement

Conversion from displacement to velocity:

$$v = 2 \pi f d \quad (1b)$$

Conversion from peak to RMS units:

$$\text{RMS} = \text{peak} \times (1/\sqrt{2}) \quad (2a)$$

Conversion from peak-to-peak to RMS units:

$$\text{RMS} = (\text{peak-to-peak} / 2) \times (1/\sqrt{2}) \quad (2b)$$

Conversion from narrowband (1 Hz bands) to 1/3 octave bands:

$$1/3 \text{ octave band amplitude} = S \times (2.08 / \sqrt{F_c}) \quad (3)$$

Where: S = summation of narrow band amplitudes over the bandwidth of interest

F_c = the center frequency of the particular bandwidth considered

$2.08 = \sqrt{(F_c/bw)}$

bw = bandwidth of the particular 1/3 octave band

amplitude for reference purposes. The converted specification is shown in Figure 8.

Vibration specifications were provided by manufacturer F for a transmission electron microscope (TEM). A transmission electron microscope works similar to a SEM but the image is formed from the electrons transmitted through the specimen. A TEM with this level of magnification is typically associated with generic VC-D criterion. The manufacturer provided different specifications if an active isolation system is utilized or if only passive isolation is included. Prior to the presentation of the tolerable vibration amplitudes, a short discussion about the variety of presentation methods, many of which were exhibited by other manufacturers, was included. The vibration data was

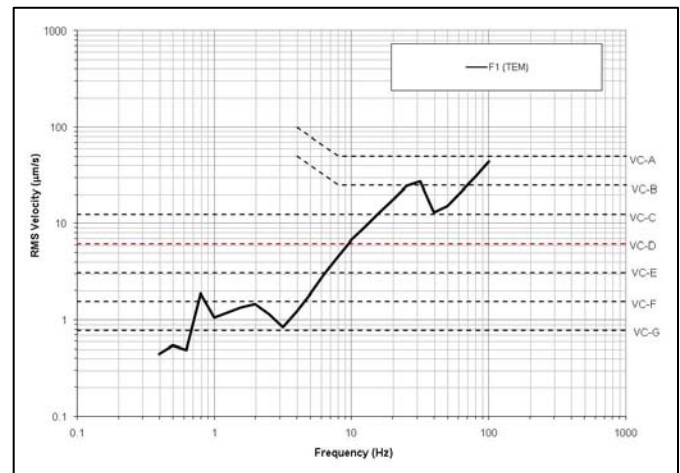


Figure 8: Converted manufacturer-provided vibration specification for F1 (TEM)

COMPARISON WITH GENERIC VIBRATION CRITERIA CURVES

As noted in the introduction to this paper, the actual equipment to be housed in a structure and the associated vibration specifications are rarely known by the structural engineer prior to commencement of design. For this reason, the generic vibration criteria curves shown in Figure 1 are commonly used for design. A comparison of the manufacturer specification with the generic vibration criteria which would be used if no other information was available is presented here. For equipment A1, the manufacturer's specification is compared to the VC-D curve recommended for equipment with magnification in this same range in Figure 2. This comparison indicates that the VC-D criteria is comparable for frequencies less than 30 Hz and is conservative for frequencies greater than 30 Hz. If active isolation is incorporated into the SEM, the VC-D vibration criterion is conservative over the entire range of frequencies between 2 to 4 times the actual manufacturer specifications. For equipment A2, the manufacturer's specification is also compared to the VC-D curve because of the magnification range of the equipment. This comparison, shown in Figure 3, indicates that the VC-D criterion is not conservative for frequencies less than 30 Hz. The same generic criteria is conservative for frequencies over 30 Hz or if an active isolation system is incorporated into the equipment.

For equipment B1, the manufacturer specifies a vibration tolerance that follows the generic VC-C curve over the range of 4 – 100 Hz and extends the tolerance of the lower range to 1 Hz as shown in Figure 4. For equipment C1, the manufacturer's specification is compared to both the VC-B and VC-C criteria as shown in Figure 5. Both generic criteria underestimate the allowable vibration amplitude for frequencies below approximately 70 Hz and could require a more specialized structural design to meet the generic criteria. The specification provided by manufacturer D is compared to the VC-B and VC-C curves in Figure 6. This generic criterion overestimates the allowable amplitude of vibrations when compared to the specification from the manufacturer for frequencies over 4 Hz. The same manufacturer's specification for a different type of equipment, D2, is compared to the generic criteria VC-B and VC-C as shown in Figure 7. For this particular piece of equipment, the generic criteria VC-C is just slightly conservative when compared to the manufacturer's specifications. The manufacturer specification for equipment, E1, is comparable to generic criteria VC-C as shown in Figure 8. For equipment F1, the manufacturer specification is compared to the generic criteria VC-D in Figure 9. The generic criterion does not accurately reflect the sensitivity of the equipment to vibration below 10 Hz but overestimates the sensitivity above 10 Hz.

DISCUSSION AND SUMMARY

Examining the vibration specifications from a variety of manufacturers for a variety of equipment types has demonstrated two important points: first, manufacturers utilize a variety of metrics and methods in developing and presenting the vibration specification for a piece of equipment; and second, the generic vibration criteria available do not always provide appropriate or conservative guidance for a specific piece of equipment.

Through an examination of only eight examples of individual vibration specifications, the full range of metrics including acceleration, velocity, and displacement were observed. The most common metric observed was velocity and this is consistent with the generic vibration criteria and the most common recommendations. However, several specifications were presented in acceleration or displacement and would require conversion to velocity for the most common structural design methodologies. A variety of amplitude measurements were also observed including RMS, peak, peak-to-peak, and even specifications that did not identify the amplitude measurement. One specification gave guidance for converting to RMS from peak-to-peak amplitudes but this would need to be applied to other specification that didn't provide this guidance. Although the generic vibration criteria are presented in 1/3 octave bands, some manufacturers developed their vibration specifications through a narrowband analysis. The narrowband analysis can introduce difficulty during the design phase because of the large number of frequencies, particularly at higher frequencies, for which the structural design must be evaluated. Through the examination of these individual specifications, it was observed that a short description of how the testing was performed or if the specification was developed in another manner such as a simple reference to the corresponding generic vibration criteria.

The second point that was demonstrated through this study was the variation between the supposed corresponding generic vibration criteria and the actual levels of tolerable vibration. It is understood that the generic vibration criteria are only meant to be used for guidance when no other more specific information is available. However, if the generic vibration criteria are utilized and assumed to be conservative, the individual specifications examined here have proved that this is not always the case. This comparison has shown that the

specifications developed by the manufacturer may even be less stringent than the corresponding generic vibration criteria. This emphasizes the importance of accurate and thoroughly developed manufacturer's specifications. It also emphasizes the importance of obtaining the vibration specification of the actual equipment that is to be housed in a structure to ensure an appropriate and economical design.

REFERENCES:

- Amick, H., Busch, T., Gendreau, M., Gordon, C. (2005), "Evolving criteria for research facilities: I – Vibration," *Proceedings of SPIE Conference 5933: Buildings for Nanoscale Research and Beyond*, August 2005.
- Amick, H. (1997), "On generic vibration criteria for advanced technology facilities," *Journal of Institute of Environmental Sciences*, v40, n5 Sep-Oct 1997, p35-44.
- Gordon, C.G. (1991), "Generic Criteria for Vibration-Sensitive Equipment," *Proceedings of SPIE - The International Society for Optical Engineering*, v 1619, 1991, p 71-85.
- Murray, T.M., Allen, D.E. and Ungar, E.E. (1997), "Floor Vibrations due to Human Activity," *Steel Design Guide Series, No. 11*, American Institute of Steel Construction (AISC).
- Ungar, E.E., Sturz and Amick, H. (1990), "Vibration Control Design of High Technology Facilities," *Sound and Vibration*, Jul, 1990, p20-27.