Generic Vibration Criteria for Vibration-Sensitive Equipment

Colin G. Gordon

Colin Gordon & Associates, 411 Borel Avenue Suite 425, San Mateo, CA 94402 USA

ABSTRACT

The vibration criterion (VC) curves, commonly used in the design of facilities which house vibration-sensitive instruments and tools, were developed by the author and his colleagues, in the early 80's, published by SPIE in 1991 and by IEST in 1993. Each of the criterion curves A through E is associated with a "line width" or "detail size" which was an attempt by the authors to describe the capabilities of the tools with which each curve might be associated. In the years since the curves were developed there have been substantial developments in tool design and isolation. In this paper the curves are reviewed in the context of present-day tools and processes. Changes are proposed where these might be justified.

Keywords: Vibration Criteria, facility design, fabrication tools, microelectronics fabrication, medical and pharmaceutical research, vibration-sensitive equipment.

1. INTRODUCTION

The criterion curves were developed in the 1980's in response for a need for design standards to accommodate a wide range of tools and instruments used by the microelectronics, medical and biopharmaceutical industries. The curves and descriptors that accompanied them were necessarily "generic" in the sense that they were intended to meet the needs of all tools within each category as best the authors could judge based on experience mingled with tool-specific specifications (often incomplete) provided by manufacturers.

As time passed the curves were extended to reflect the needs, or projected needs, of technology and tool developments, primarily in the microelectronics industry. The most recent technical paper on the curves, describing their history and justification, was presented at a SPIE conference in November 1991 and published in the proceedings of that conference (Ref. 1). A paper by Amick (Ref. 2) discusses the VC curves and other generic criteria and many of the issues involved in processing vibration data. The VC curves are published in design documents published by the Institute of Environmental Sciences and Technology (Ref. 3) and the American Institute of Steel Construction (Ref. 4).

The VC curves are now widely accepted throughout the world as a basis for designing and evaluating the performance of microelectronics fabrication facilities where continuity of vibration-free tool performance is essential. In this paper the curves and their descriptors are reviewed in the light of continued and projected future tool developments taking into account experience on past and present projects. Some of their limitations are discussed.

2. THE VC CURVES

In their present form the criteria take the form of a set of one-third octave band velocity spectra, labeled vibration criterion curves VC-A through VC-E. These are shown in Figure 1, together with the International Standards Organization (ISO) guidelines for the effects of vibration on people in buildings. The criteria apply to vibration as measured in the vertical and two horizontal directions. The application of these criteria as they apply to people and vibration-sensitive equipment are described in Table 1.

A general description of the curves, and their intended method of use, is as follows:

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1) The vibration is expressed in terms of its root-mean-square (rms) velocity (as opposed to displacement or acceleration). It has been found in various studies that while different items of equipment (and people) may exhibit maximum sensitivity at different frequencies (corresponding to internal resonances), often these points of maximum sensitivity lie on a curve of constant velocity.

2) The use of a proportional bandwidth (the bandwidth of the one-third octave is twenty-three percent of the band center frequency) as opposed to a fixed bandwidth is justified on the basis of a conservative view of the internal damping of typical equipment components. Experience shows that in most environments the vibration is dominated by broadband (random) energy rather than tonal (periodic) energy. In such an environment measurement bandwidth is critically important.

3) The fact that the criterion curves allow for greater vibration velocity for frequencies below 8 Hz reflects experience that this frequency range, in most instances, lies below the lowest resonance frequency of the tool structure. Relative motions between the components are, therefore, harder to excite and the sensitivity to vibration is reduced.

4) For a site to comply with a particular equipment category the measured one-third octave band velocity spectrum must lie below the appropriate criterion curve of Figure 1.

These equipment criterion curves have been developed on the basis of data on individual items of equipment and from data obtained from measurements made in facilities before and after vibration-related problems were solved. The curves are generic in the sense that they are intended to apply to broadly defined classes of equipment and processes. **They are intended to apply to the most sensitive equipment within each category that is defined**.

The criteria assume that bench-mounted equipment will be supported on benches that are rigidly constructed and damped so that amplification due to resonances is limited. They take into account the fact that certain types of equipment (such as SEM's) are often supplied by the manufacturer with built-in vibration isolation.

The criteria are for guidance only. The "detail sizes" given in Table 1 appear to represent experience at the time of writing. They reflect the fact that the quality of design and of built-in isolation in most equipment tends to improve as dimensional requirements become more stringent. In some instances the criteria may be overly conservative because of the high quality of built-in isolation. Thus, for instance, many steppers used in photolithography are, currently, relatively insensitive to vibration.

When measuring for compliance with these criteria one must take into account the "nature" of environment that is being measured:

1) When the environment is relatively constant in time and spatially uniform—generated for instance by continuously running mechanical systems (fan, pumps, etc.) or by heavily traveled highways—it is generally adequate to measure the "energy average" vibration levels. Levels can be measured at multiple locations, if the area being evaluated is large, and the collective data can be summarized statistically. It is considered reasonable to classify the VC performance based on the "average plus one standard deviation" level at each frequency.

2) When the environment is not constant in time—impacted for instance by walkers (footfall excitation), or nearby trucks—it may be necessary to measure the "maximum rms" (sometimes called "peak hold") vibration levels.

A comprehensive discussion of data processing methods is given in Ref (2).

3. OTHER GENERIC CRITERIA

A number of different criteria for vibration-sensitive tools have been developed over the years. Few of them are truly generic in the sense that they can be used to embrace the requirements of a wide range of tool types. Two candidates, one existing and one under development are described below.

3.1 Medearis Time Domain Method

Medearis (Ref. 5) recommends generic criteria for vibration-sensitive equipment based on "time domain" as opposed to "frequency domain" peak-to-peak displacement measurements. The frequency range of measurements is not defined. He suggests limits of 2.5 microns (100 microinches) and 7.5 microns (300 microinches) for microelectronics facilities and science laboratories, respectively. His criteria are not reconcilable with the fact that most tool makers, recognizing that their equipment is not equally sensitive at all frequencies, provide siting specifications in the form of frequency domain spectra.

3.2 Ahlin Response Spectrum Method

Ahlin (Ref. 6) is currently developing a new measurement and evaluation methodology based on the concept the response spectrum, used extensively by structural dynamicists in seismic design engineering. The methodology has promise but is, currently, neither supported by instrumentation nor experience.

4. CRITICAL REVIEW OF THE VC METHODOLOGY

The VC criteria curves have been used extensively by the microelectronics industry and research communities for the past fifteen years. In some cases, tool makers have adopted the criteria as a basis for "siting" specifications for their equipment. The author and his colleagues have used the criteria as the basis of design for several hundred chip fabrication facilities. This experience shows, clearly, that the criteria work—that tool operational problems, due to vibration, can be avoided if vibration conditions on the floor of the facility comply with the criterion curve appropriate to the process.

In spite of their widespread use, some aspects of the VC curves have been questioned. Some of the issues raised are discussed in the following paragraphs.

4.1 Spectral-Domain versus Time-Domain

Vibration-related problems with tools generally arise at the resonance frequencies of structural components within the tool. It is at such frequencies that components vibrate most strongly, with the likelihood of image distortion due to differential motions between components. The frequency sensitivity of tools is recognized by most tool vendors who, almost without exception, specify siting requirements in the frequency domain. Examples of current tool specifications are given in Figures 2, 3 and 4*. Time-domain amplitude limits, which consider the sum-total of all frequencies without discrimination, make little sense unless specific frequency ranges are quoted for the measurement system.

4.2 Velocity versus Displacement (or Acceleration)

The three common metrics of displacement, velocity and acceleration are absolutely related to each other by frequency. Basically, therefore, each metric is equally valid and one can convert from one metric to the other by post-processing of the measured data. Velocity appears as a convenient metric for at least three reasons:

1) Photolithography processes are dependent upon maintaining a stable image during the exposure time. The limit, therefore, is a limit on image velocity. One can argue also that visual interpretation of images seen through a microscope are dependent upon the velocity of image movement, rather than displacement.

2) Many vendor specifications are given in terms of velocity, others are given in displacement or acceleration. Velocity is a "happy compromise".

3) Velocity lies midway, in terms of conversion, between displacement and acceleration and represents, therefore, a convenient choice.

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* Interpretation of vendor specifications is not always easy since, often, bandwidth information is not given and frequency limits are not clearly stated. Sometimes the specifications are not based on the results of physical testing.

4.3 One-Third Octave Band versus Narrowband Spectra

Vibration environments on floors and "greenfield" sites are, generally, dominated by random broadband energy. Pure tone components may arise only due to poorly isolated mechanical equipment (fans, pumps, etc.). The bandwidth of the filters (or effective filters) used in frequency-domain measurements are critically important when broadband energy is involved; the broader (wider) the filter the higher will be the measured levels.

The VC curves are based on one-third octave band measurements, where the filter width bears a constant proportion (0.23) to the band center frequency. Use of the one-third octave methodology is defendable for a number of reasons:

1) It adequately describes the response of a resonator to broadband excitation assuming a reasonable value of damping.

2) It is used by a number of tool vendors in their siting specifications.

3) It substantially simplifies the complexity of a typical vibration spectrum, especially one containing significant tonal components.

Narrowband spectra, on the other hand, are invaluable when diagnosing the causes and sources of floor vibration.

4.4 Shape and Frequency Range

The VC curves extend from 4 Hz to 100 Hz (80 Hz in many data reports). At the time the curves were developed the 4 Hz lower limit made sense since equipment, at that time, exhibited negligible sensitivity to low frequency inputs. Those few vendors who quoted vibration specifications for their tools rarely defined requirements below about 5 Hz.

With the increasing use of pneumatic isolation systems (air springs) as an integral part of the tool, concern has increased about vibration conditions at the resonance frequencies (1 to 3 Hz) typical of these isolators. At resonance, the isolator amplifies the floor vibration and the possibility exists that tool operation could be affected. Figures 2, 3 and 4 show several specifications that extend below 4 Hz.

There is less concern about the upper frequency limit of the VC curves. Some manufacturers do extend their requirements above 100 Hz but there is significant evidence that vibration at these frequencies is rarely a problem.

In their present form the VC curves impose less stringent vibration limits for frequencies below 8 Hz. In the 4 to 8 Hz range the limit, in effect, is that of constant acceleration instead of constant velocity.

Arguments have been put forward in recent years that, in the case of pneumatically isolated equipment, not only should the range of the curves be extended downwards, to 1 Hz say, but that the constant velocity limit should be retained throughout the range. A suggested revision to the shape of the generalized VC curve has been published by Ungar, Sturz and Amick (Ref. 7). It is shown in Figure 5. No change is suggested in the case of tools that do not use pneumatic isolation.

5. GENERIC CURVE SELECTION

Table 1 attempts to describe the application of the VC curves in terms of "detail size" (line width in the case of microelectronics fabrication) and the general type of equipment for which each curve is appropriate.

The detail sizes are clearly approximate and dependent upon the degree of sophistication used in the structural and isolation design of the individual tool. **One must constantly bear in mind the fact that the curve descriptors are intended to apply to the most sensitive tools within each category**. Since tools are constantly changing and new tools introduced, the "most sensitive" limit is a constantly moving target.

A few words need to be said about the detail sizes assigned to the most stringent curves, VC-D and VC-E. It is a fact that the tool maker must develop his tool in his own facility, which typically will have a slab-on-grade floor located, often, in a lightindustrial zone with heavily-traveled roads and highways. Silicon Valley in Northern California is such an area. It is likely that the tool maker's floor will carry ambient vibration amplitudes in the range VC-E to VC-D. One can argue, therefore, that present and future tools can never be more sensitive than allowed by the VC-E to VC-D range. If the basic tool itself is more sensitive than these curves the tool vendor will, necessarily, need to incorporate additional isolation as an integral part of the tool.

The "Description of Use" texts are very generally written. Slightly different versions of these texts have been introduced by Murray, Allen and Ungar (Ref. 4) and Ungar, Sturz and Amick (Ref. 7). Clearly, these descriptors should not be used blindly. Advice should be sought from the tool maker(s) as regards their requirements, and allowance should be made for future technology and future tools over the planned life of the building.

A number of issues must be considered when selecting the appropriate criterion curve for a new or retrofitted building. Some of these are discussed below:

5.1 Base versus Operating Condition

"Base" vibration conditions apply to the vibration environment prior to installation and/or start-up of tools and equipment used in "normal" production. Tools can often create vibration associated, for example, with the vacuum pumps used by electron microscopes. The base building condition is the most critical condition since it represents a "lower limit" of performance in the same way that a building HVAC noise imposes a lower limit on office noise. As tools are introduced, vibration amplitudes will generally increase to an extent dependent upon the care taken in vibration isolation of the tools and their accessories (pumps, etc.). Examples of "before" and "after" environments are shown in Figures 7 and 8.

5.2 Facility Maturation

Almost inevitably, vibration environments will deteriorate as time passes due to aging of vibration generating equipment, misalignment of isolation hardware, growth of vibration-generating activities around the plant, etc. The worst effects of maturation can be measured and, perhaps, controlled by installing a computer-based monitoring system but some degree of deterioration is almost inevitable. Some parts of the changes shown in Figures 7 and 8 are certainly due to aging.

5.3 Multiple Criteria and Layout Flexibility

The microelectronics industry, especially, is subject to rapid change both in terms of tools and process layout. In the past there has been a tendency by this industry to design all parts of the fabrication cleanroom to a uniformly strict vibration criterion. This allows maximum flexibility of present and future layout; the most sensitive tools can be placed anywhere within the cleanroom envelope. In an attempt to reduce facility costs there has been a recent move towards minimizing the area of floor designed to the most stringent criterion and using a more relaxed criterion for non-sensitive fabrication. Of course, as a result, the layout flexibility of the facility is reduced.

5.4 Facility Costs

The choice of vibration criterion affects the cost of the facility. Facility costs have become a major parameter in new facility planning in the past several years. Thus, whereas several years ago facility cost was less important than issues of flexibility, future technology trends and conservatism, now the situation is markedly changed, at least in some areas.

5.5 Future Trends

It has been argued earlier that future tools and instruments, no matter their capabilities in terms of resolution and processing technology, will never require vibration environments significantly better (lower) than the VC-E to VC-D range. It is very likely that the 0.1 micron limit specified for VC-E will be extended downwards as time passes. Performance in the VC-E to VC-D range is exceptionally difficult to achieve on column-supported floors of conventional design.

6. CONSERVATISM

Figures 2, 3 and 4 demonstrate the enormous range of sensitivities quoted by tool manufacturers for tools that serve, nominally, the same purpose. It is the most sensitive of these and other tools, in all categories, that forms the basis of the VC curves. The nature of tool-and-technology development is such that most facilities must be able to accept the most sensitive tools now and in the future. Even if one has doubts about the physical validity of a particular tool specification—perhaps the tool manufacturer has never physically tested the tool under controlled vibratory inputs—often the tool warrantee will be conditional upon demonstrating compliance with the specification.

There is little doubt, therefore, that designing a facility to one or other of the VC curves, especially the most stringent curves VC-D and VC-E, will result in performance that significantly exceeds the needs of the particular tool set that may be used at any moment of time. Similarly it is very likely that a facility that was designed to manufacture product with a detail size (line width) of 0.3 micron, say, will continue to successfully manufacture product as line widths decrease to 0.18 micron and even lower.

At the present time, therefore, the VC curves are quite conservative and are, therefore, able to handle reasonable "exceedances" imposed by tool installation vibration and the effects of aging.

7. CONCLUSIONS

The VC curves still appear to provide a valid and useful generic basis for evaluating sites and designing structures that will support vibration-sensitive equipment and processes. Suggestions have been made, by others, that the low-frequency form of the curves might be modified to handle the particular needs of pneumatically isolated equipment. This suggestion is currently being studied.

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6) Response Equivalent Peak Velocity—A New Method for Description of Vibration Environment for Sensitive Equipment in Buildings, Kjell Ahlin, presented at SPIE's International Symposium on Optical Science, Engineering and Instrumentation, July 1999.

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Table 1: Application and interpretation of the generic vibration criterion (VC) curves (as shown in Figure 1)

Criterion Curve (see Figure 1)	Max Level (1) micrometers/ sec,rms	Detail Size (2) microns	Description of Use
Workshop (ISO)	800	N/A	Distinctly feelable vibration. Appropriate to workshops and nonsensitive areas.
Office (ISO)	400	N/A	Feelable vibration. Appropriate to offices and nonsensitive areas.
Residential Day (ISO)	200	75	Barely feelable vibration. Appropriate to sleep areas in most instances. Probably adequate for computer equipment, probe test equipment and low-power (to 20X) microscopes.
Op. Theatre (ISO)	100	25	Vibration not feelable. Suitable for sensitive sleep areas. Suitable in most instances for microscopes to 100X and for other equipment of low sensitivity.
VC-A	50	8	Adequate in most instances for optical microscopes to 400X, microbalances, optical balances, proximity and projection aligners, etc.
VC-B	25	3	An appropriate standard for optical microscopes to 1000X, inspection and lithography equipment (including steppers) to 3 micron line widths.
VC-C	12.5	1	A good standard for most lithography and inspection equipment to 1 micron detail size.
VC-D	6	0.3	Suitable in most instances for the most demanding equipment including electron microscopes (TEMs and SEMs) and E-Beam systems, operating to the limits of their capability.
VC-E	3	0.1	A difficult criterion to achieve in most instances. Assumed to be adequate for the most demanding of sensitive systems including long path, laser-based, small target systems and other systems requiring extraordinary dynamic stability.

Notes:

(1) As measured in one-third octave bands of frequency over the frequency range 8 to 100 Hz.

(2) The detail size refers to the line widths for microelectronics fabrication, the particle (cell) size for medical and pharmaceutical research, etc. The values given take into account the observation that the vibration requirements of many items depend upon the detail size of the process.

Figure 1: Generic Vibration Criterion (VC) Curves for Vibration-Sensitive Equipment - Showing also the ISO Guidelines for People in Buildings (see Table 1 for description of equipment and uses)

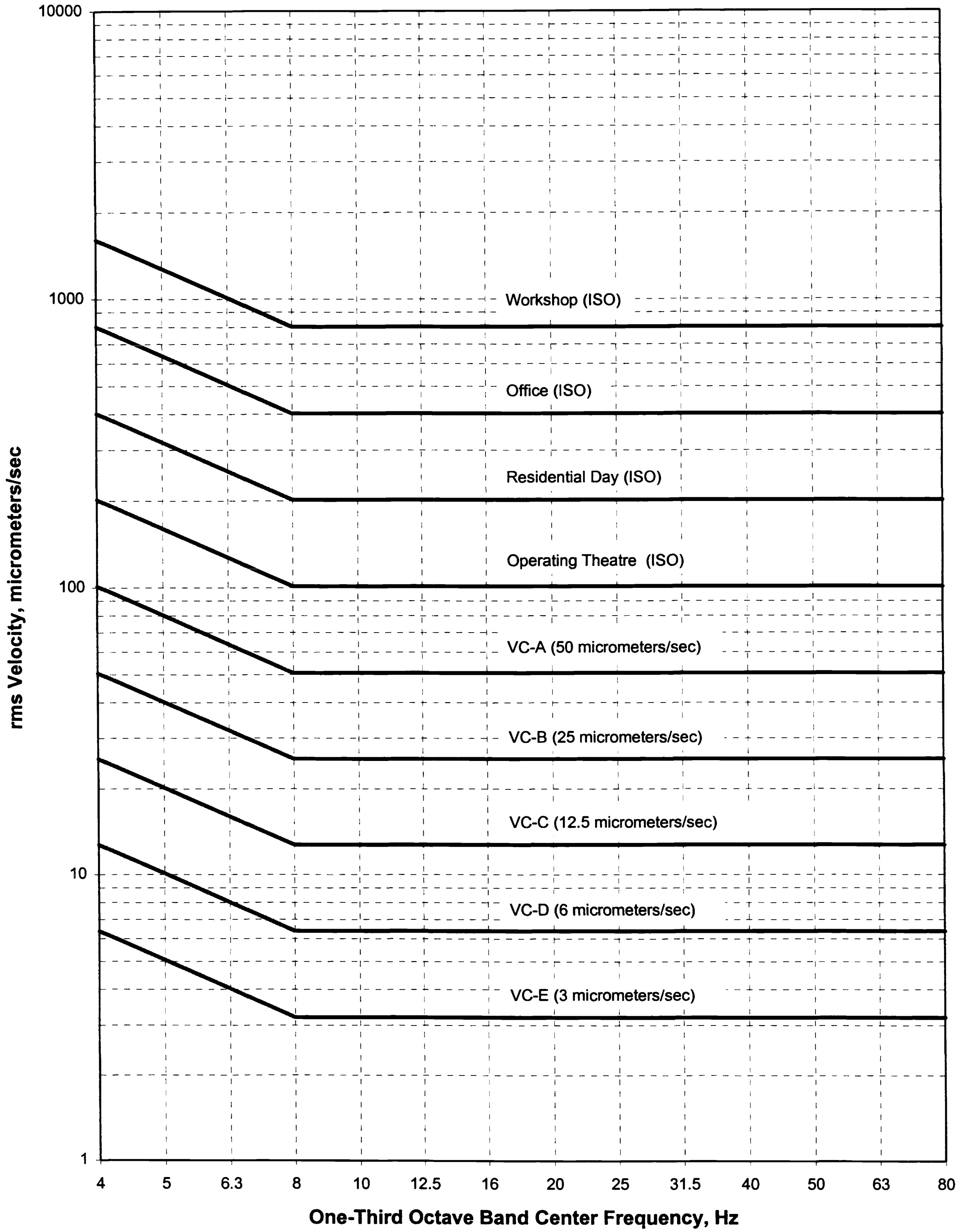


Figure 2: Vibration Specifications for Three Electron Microscopes (EM) versus Generic Vibration Criterion (VC) Curves

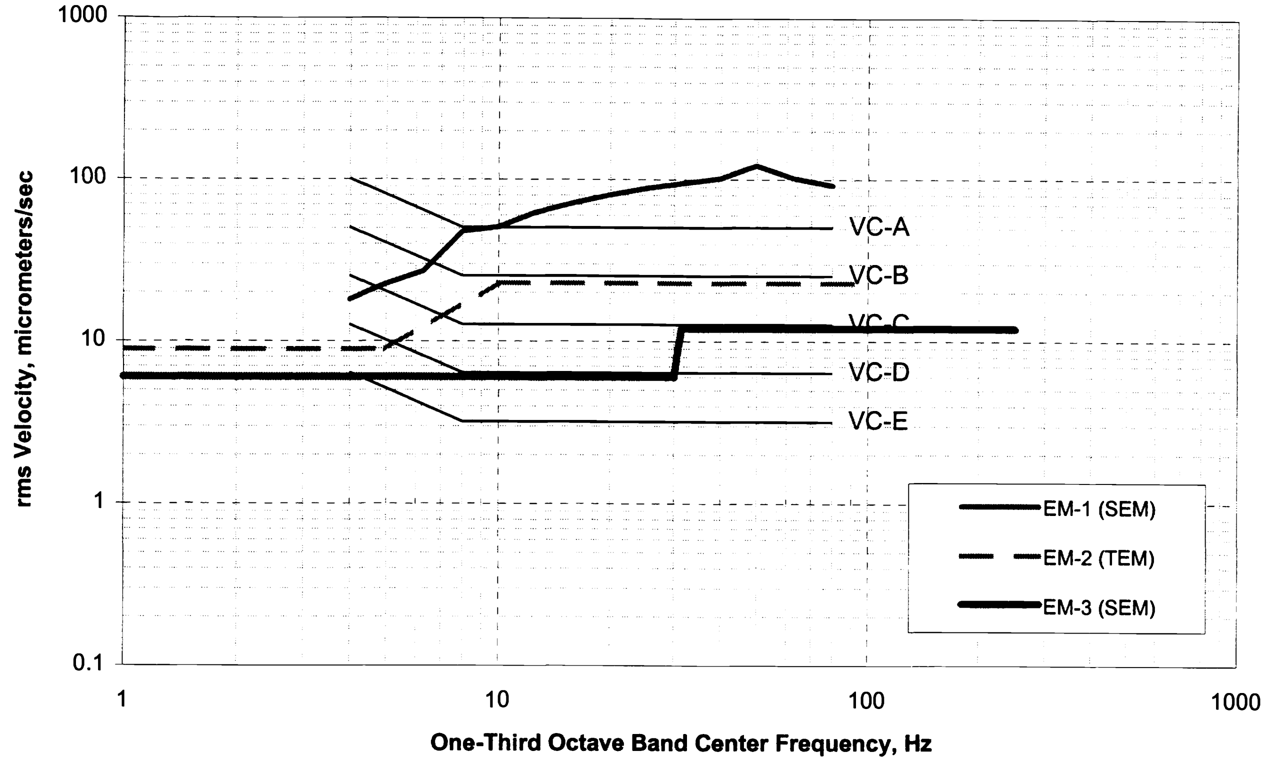


Figure 3: Vibration Specifications for Three Photolithography Scanners versus Generic Vibration Criterion (VC) Curves

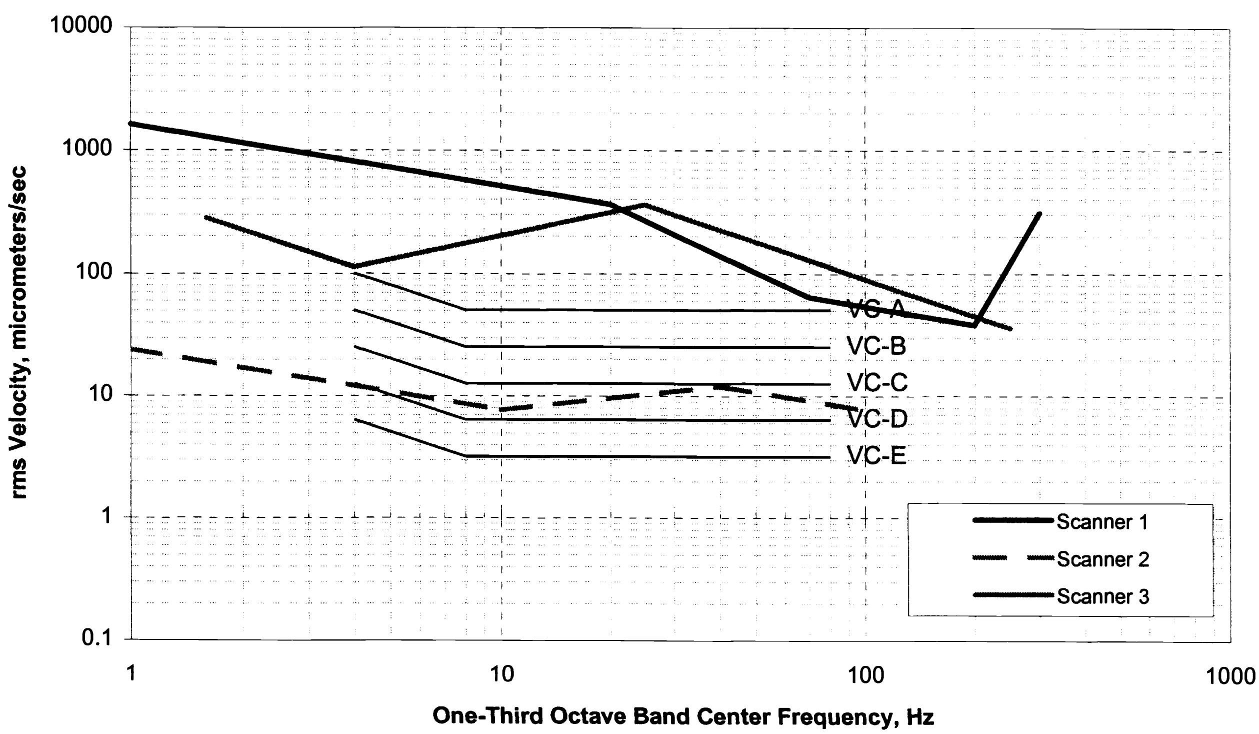


Figure 4: Examples of Vendor Specifications for a Typical Tool Set Used in 0.25 to 0.7 micron Fabrication

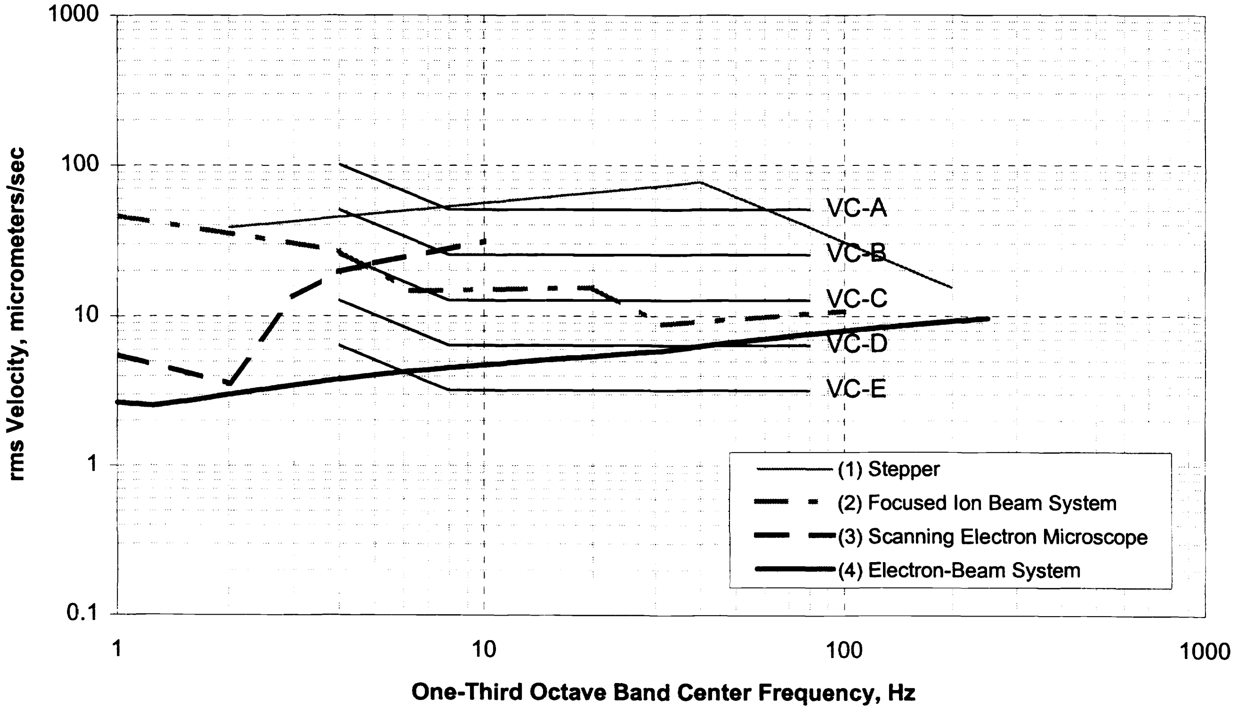


Figure 5: General Criteria Curve Form Suggested by Ungar et. al. (3) to be Used with Values of Table 1. Solid curve pertains to equipment without pneumatically-isolated systems, dashed curve to equipment with low-frequency pneumatic isolation.

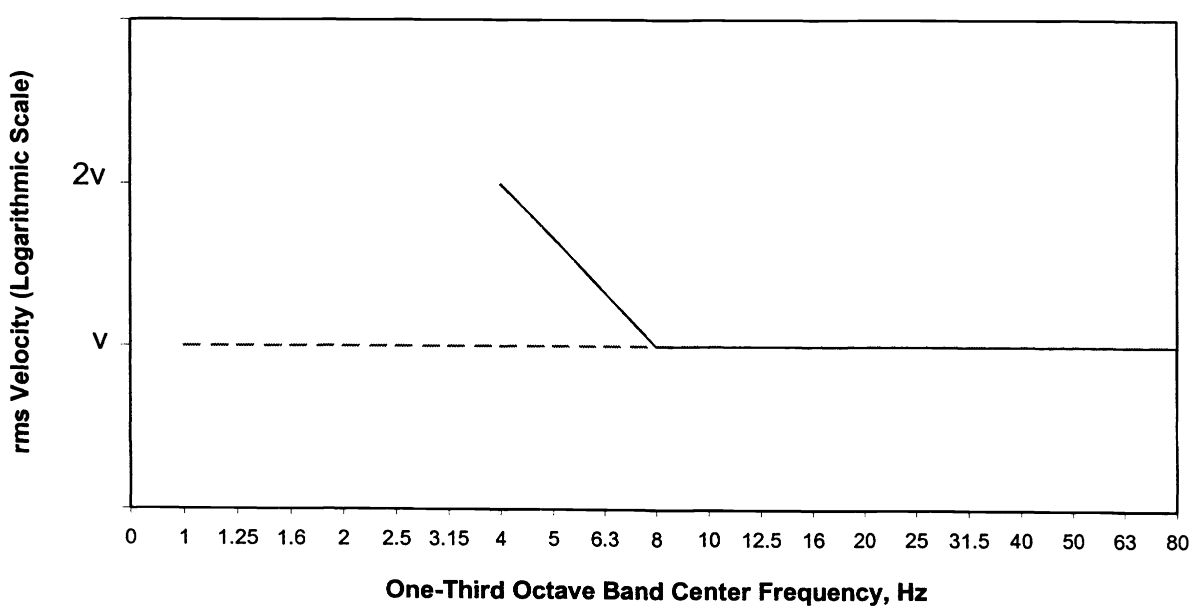


Figure 6: Comparison of Pre- and Post-Startup Vertical Vibration

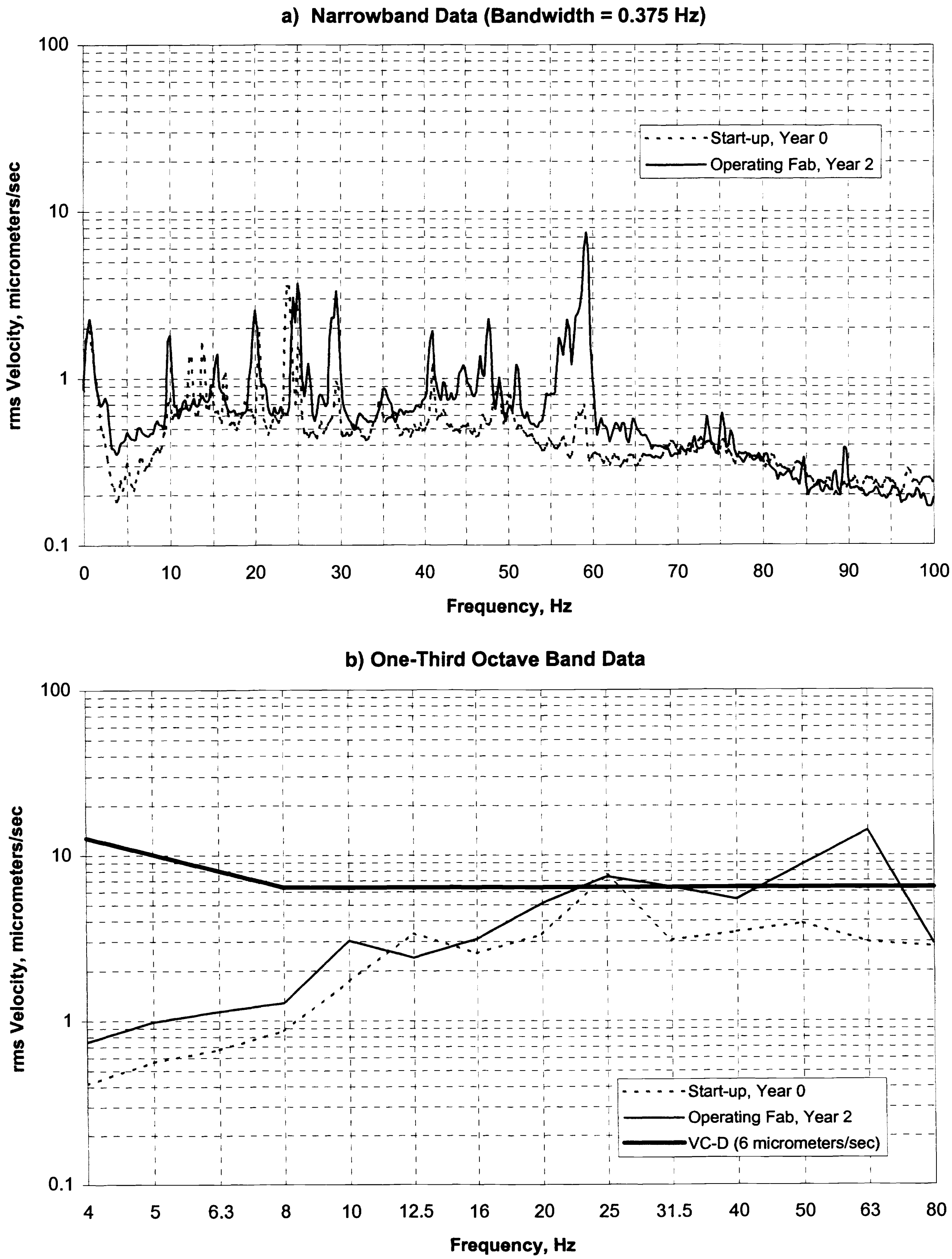
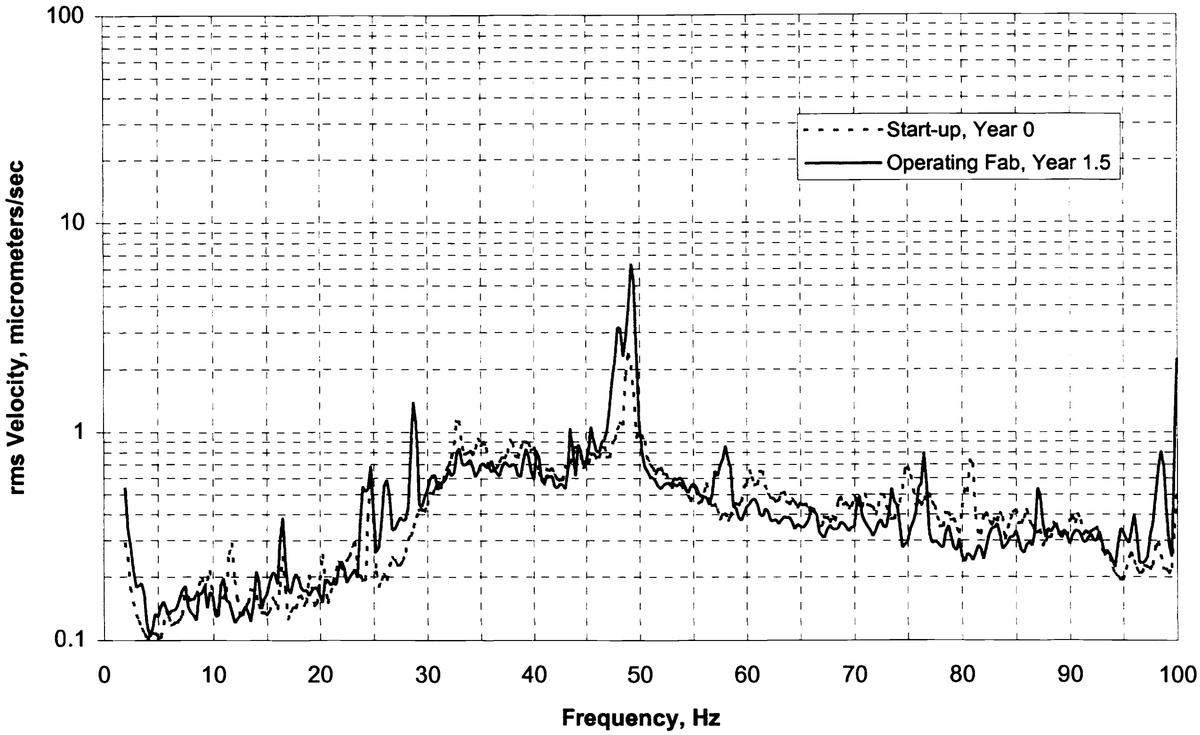


Figure 7: Comparison of Pre- and Post-Startup Vertical Vibration

a) Narrowband Data (Bandwidth = 0.375 Hz)



b) One-Third Octave Band Data