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Centile spectra, measurement times, and statistics of ground vibration

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ABSTRACT: Facilities for advanced technology—particularly nanotechnology—impose very stringent requirements on the quality of the site. Ambient ground vibrations are among the most critical factors to consider when selecting a site. Commonly-accepted vibration criteria are available and they, in turn, dictate many of the measurement parameters such as bandwidth, frequency range, etc. However, there are still many options available to the analyst for representing time-varying statistics. This paper reviews some of the statistically-based protocols for data representation for these facilities.

1 Introduction

A growing number of structures are being designed and constructed specifically to house and support advanced technology. Advanced technology (or "high tech") facilities can include those for semiconductor production, biotechnology R&D, and metrology (the technology associated with precise measurements). The newest entry into this group is nanotechnology.

Nanotechnology offers potential benefits that may be as revolutionary as the space program of the 1960s, the advent of computers, or even the Industrial Revolution. Almost everyone who has heard the word knows it deals with small things, but not everyone appreciates the extent to which it impacts advanced technology fields and, by default, the world of the design professional.

The sophisticated working environments required for nanotechnology facilities pose big challenges to their designers and constructors. The workplace environmental requirements may include temperature and humidity control, air cleanliness (i.e., particulate and chemical contamination), biohazard containment, limits on electromagnetic fields, special electrical power conditioning, and vibration and noise control. Most of these design aspects have evolved from the special needs of working at exceedingly small scales. Very few existing buildings can meet these demands—new construction is generally required.

1.1 Vibration-sensitive facilities

Nanotechnology has been defined as research and technology development dealing with particles and systems with dimensions of approximately 1 to 100 nanometers. In many cases, the environment typical for semiconductor production is appropriate. In other cases, it is not stringent enough.

It has become common practice to use a limited set of published "generic" vibration criteria which may be selected for a facility or space within a facility based upon the most demanding equipment likely to be used in a given process. An assessment of a proposed site is then based upon the vibration criterion associated with the most demanding application.

The most popular of the generic criteria are shown graphically (as velocity spectra)[1] in Figure 1 [IEST (2005), Amick, *et al.* (2002)]. Many of these criteria have been in use for 20 years in several advanced technology communities, providing an "experience base", and have been applied to the design several nanotechnology facilities.

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[1] The generic criteria in Figure 1 are given in terms of RMS velocity amplitude as processed in one-third-octave bands of frequency. See Amick (1997).

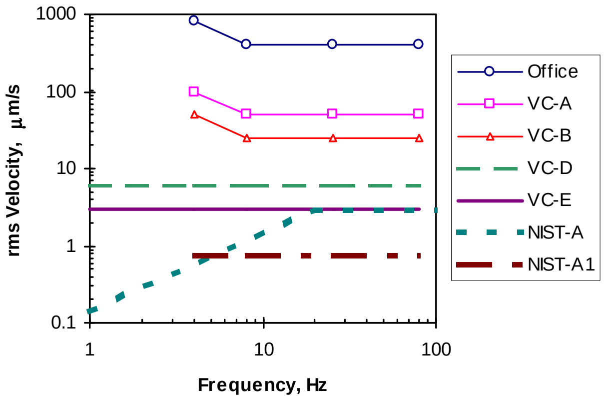

Figure 1. Common generic vibration criteria commonly used for nanotechnology facilities, in the form of velocity spectra.

The most highly-sensitive spaces—in which submicron and molecular-scale processes are carried out—use criterion VC-D or VC-E (both routinely used worldwide for semiconductor facilities). There are some even more demanding spaces requiring the alternative NIST-A criterion, developed for metrology laboratory space at the Advanced Measurement Laboratory (AML) at the USA's National Institute of Standards and Technology (NIST) in Gaithersburg, Maryland. NIST-A is more stringent than VC-E at frequencies below 20 Hz [Amick, *et al.* (2002)].

The success of facilities to be designed to VC-D, VC-E or NIST-A will depend to a great extent upon the adequacy of their sites. Thus, it is customary to assess the site vibrations as part of the site selection or design process. The site survey may be simple or extensive, as dictated by the requirements of the project. Simply stated, it should capture the vibration statistics of the site that might impact the work to be done in the facility. It should include factors that will be present throughout the life of the facility, such as road and rail traffic, and exclude factors that will not be present, such as temporary construction. These issues are discussed elsewhere [Gendreau & Amick (2005), Amick, *et al.* (2005)]

The analyst performing a site survey may be presented with several decisions. Site vibrations will vary with time and will tend to be random. How is the frequency variation and temporal variation represented? The site may be large, so several measurement locations may be required to represent the site. How is the spatial variation represented? How are transient vibrations—such as those due to road or rail traffic—represented and compared with the "steady-state" vibrations? How might one compare several sites for a facility? How might the vibrations at one site be compared with a population of similar sites? All of these questions will be addressed in the sections that follow.

2 Representing frequency content

This is perhaps the easiest statistical variable to handle. It is usually defined by the criterion being used. The VC-D, VC-E and NIST-A criteria all use rms velocity spectra as measured in one-third octave bands of frequency, at frequencies between 1 and 100 Hz [Amick *et al.* (2002)]. In this representation, the bandwidth is 23 percent of the center frequency of each band. It approximates the half-power bandwidth associated with an oscillator with 10 percent of critical damping [Amick (1997)].

At a given site, there will tend to be predominant frequency content, a mix of random and single-frequency components. In the absence of mechanical equipment—usually from nearby buildings—the site vibrations will be predominantly random. Quite often the spectrum will appear as a "hump", the frequency of which may depend on site conditions. It is not unusual for transient vibrations—such as those from trains—to have a different predominant frequency.

3 Representing temporal variation

Random site vibrations are random over time as well as over frequency. Conventional signal processing assumes that a spectrum may be used to represent time-varying random vibrations if they are *stationary*, with an integration time that is large enough to ensure that spectra taken over two different times are nearly identical. However, site vibrations may not conform to this definition of stationarity. In this instance, it may be useful to use centile spectra to represent both frequency content and statistical content. Figure 2 shows a representative set of centile spectra for the suburban site of a research facility, measured over a 30 min period during the middle of the day. There was a freeway about 0.5 km distant and on-site vehicle traffic. The six curves—starting at the top—represent the spectra that are exceeded 1%, 5%, 10%, 20%, 50% and 90% of the time. The predominant frequency at this site is 12.5 Hz.

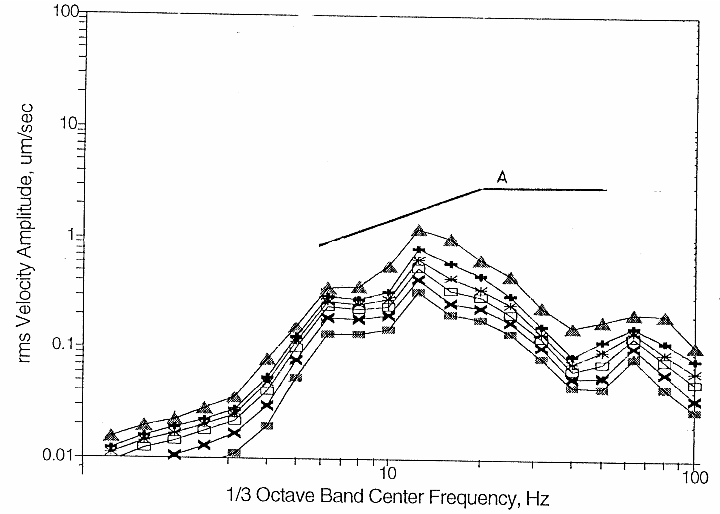

Figure 2. Typical centile spectra for a suburban site.

Figure 3 shows the 20 Hz component of vibrations at an urban site near three rail lines, processed with averaging times of 4, 32 and 60 sec. The peaks represent three train passages, plus some other unidentified transient events. The ambient spectrum is dominated by the 40 Hz component; the train passages produce vibrations centered on 20 Hz (and to a lesser extent, 6.3 and 8 Hz). The segments between 0 and 30 sec, and between 60 and 90 sec are approximately stationary with the longer integration times.

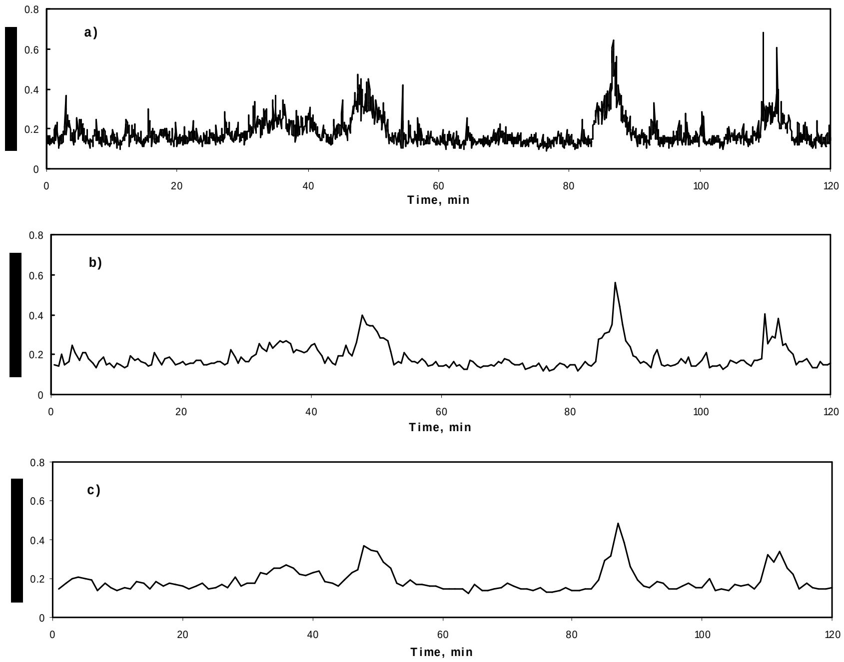

Figure 3. Vibrations measured over two hours, 20 Hz component, processed with integration periods of 4s, 32s, and 60s. Peaks correspond to train passages.

The statistical distribution of the data in Figure 3 may be presented in terms of percentile curves, showing the percent of time a given amplitude has been exceeded. Figure 4 shows this representation for the three integration times in Figure 3. The primary difference at the left end is limited to the percentiles less than 10%. There is a notable difference between the 4 sec integration curve and the other two at percentiles greater than 50%, but the 32 sec and 60 sec integration times yield nearly identical curves. This indicates that the 32 sec integration time is adequate to represent stationarity 90% of the time.

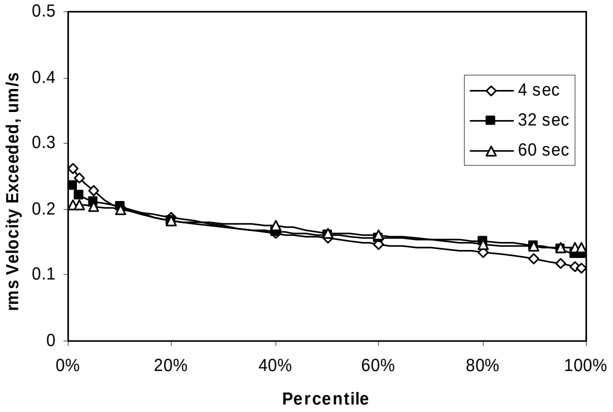

Figure 4. Statistical distribution of 20 Hz component in "steady-state" segment between 0 and 30 min.

The curve from Figure 4 for 32 sec integration time is compared with the statistical distribution of the entire 2 hour record in Figure 5. The impact of the rail passages is shown at percentiles less than 50%; the curves are nearly identical at higher percentiles. The periods in Figure 1 during which the vibrations rise above the background "ambient" represent about one-half of the total two-hour sample. The conclusion to be drawn is that the trains have a measurable impact on the site about half of the time. If a particular vibration criterion applies to 20 Hz vibrations this analysis provides a means to show the percent of time that the criterion is exceeded (say, 5% of the time if the criterion is 0.3 μm/s).

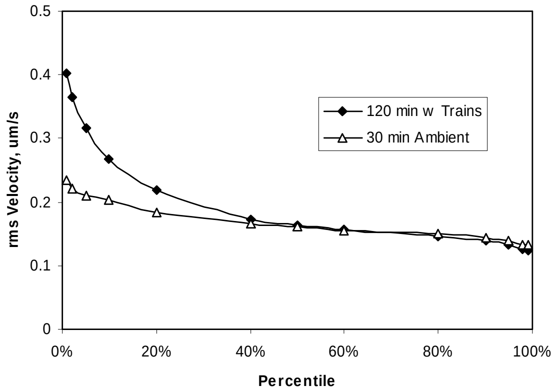

Figure 5. Comparison of statistical distribution of 2 hr period with the "ambient" or approximately "steady-state" segment between 0 and 30 min (20 Hz band, 32 sec integration time).

The log standard deviation of the series of rms amplitudes at a single frequency may be used to define the statistical variation of the amplitude. Figure 6 shows the effect of integration time on this quantity. The 20 Hz component has a log standard deviation less than 2 dB at all integration times greater than 4 sec, but it has decreased to only 1 dB at 60 seconds. The best-fit curve may be extrapolated to suggest that an integration time of about 1000 sec would be required to achieve a log standard deviation of 0 dB. An integration time of about 500 sec would produce the same result for the 8 Hz component.

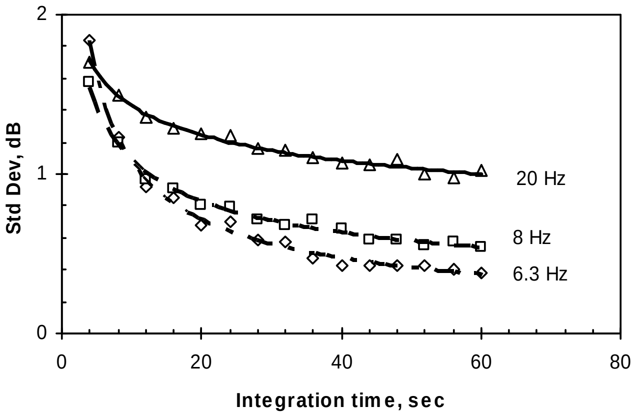

Figure 6. Effect of integration time on the log standard deviation of the 30 min "ambient" segment at the start of the 2 hr measurement period.

The variation at the left end of the curves (1%) in Figure 4 indicates that the maximum is somewhat sensitive to the integration time. The integration time will also influence the observed maximum, as shown in Figure 7. An integration time of 4 sec produced a maximum in the 20 Hz band of about 0.7 μm/s, but only about 0.055 for an integration time of 60 sec.

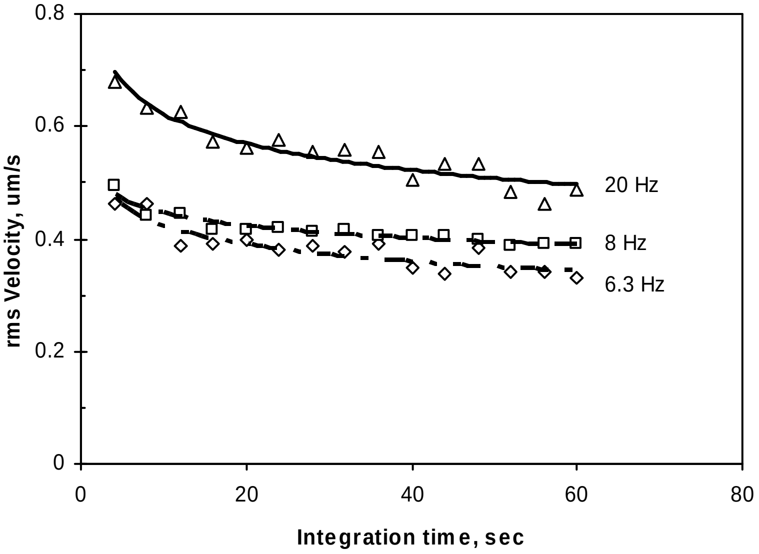

Figure 7. Effect of integration time on the maximum in the 2 hr measurement period.

4 Representing spatial variation

It is common for vibration amplitudes to vary with location over a large area. In some cases, the variation represents the proximity to sources. In others, the variation is a secondary effect due to the temporal variation in the vibrations of the surface and the difference in sampling times. Regardless, the objective is usually to compare to some criterion the statistical representation of the whole. A comparison using the average of the site would be unconservative. Using the maximum may be overly conservative.

Our practice is to carry out measurements at a statistically significant number of locations (generally between 5 and 20), and then carry out a statistical analysis on the measured spectra. The large area is typically represented by the spectrum calculated from the log mean plus the log standard deviation [Amick, *et al.* (2005)].

5 Representing multiple sites

Occasionally during the site selection process there is a need to compare sites. This has arisen in two contexts. At times, it may be necessary to compare two sites in a manner more refined than a simple comparison of two spectra. In other instances it may be useful to know how a site compares to a group of other sites: Is it among the best? Among the worst? Average? The following two sections address approaches to these analyses.

5.1 Comparing two sites

Figure 8 shows the statistical distribution of two candidate sites, A and B. The horizontal axis is a probability axis, which tends to stretch the extrema at each end, much as a logarithmic axis does at the left end. This comparison shows that the vibrations at Site B exceed those of Site A about 10% of the time, but are less than those of Site A about 90% of the time. This presentation format allowed the scientists who would occupy the facility to consider whether they were more concerned with short-term extrema or long-term stability. (They chose Site A. However, other applications might prefer the environment that was "quieter" the majority of the time, Site B.)

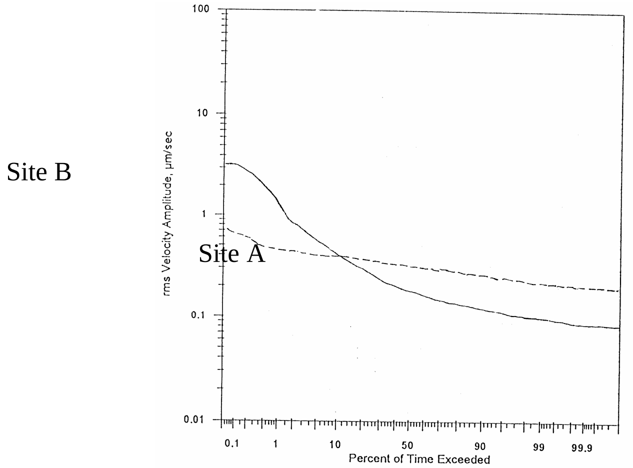

Figure 8. Use of two centile distribution curves to compare two sites.

5.2 A family of sites

Nanotechnology is currently the hottest topic in research. A variety of research organizations are expending considerable funds to build the special facilities required for much of this work. Many of these are speculative—the institutions have only a nebulous idea of the potential areas for which they might be well positioned, and hope to use the new facility to attract desirable candidates. It is not unusual to see the facility's environment (including vibrations) used as a lure.

Two of recent entries into the design arena wanted to know how their sites compared to sites of other nano R&D facilities. In order to preserve confidentiality of the twelve sites for which the authors had site data (each represented by a log mean plus log standard deviation spectrum, which we denote as Mean+SD), a statistical approach was employed. The statistical representation shown in Figure 9 was developed for the vertical data. A similar representation was developed for horizontal data. Considering each frequency separately, the population of Mean+SD data is enclosed by the maximum and minimum curves. The mean, along with the mean plus/minus one standard deviation, are plotted between the upper and lower bounds.

It may be observed that all of the sites meet VC-E (with the exception of one site at 10 Hz), but that many sites do not meet NIST-A. This has become one of the points of pride with owners who can claim to meet the NIST requirement.

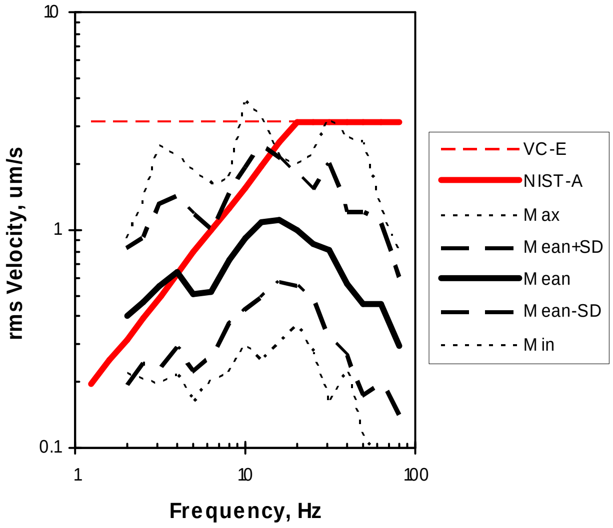

Figure 9. Statistical representation of the vertical vibration performance of sites for 12 nanotechnology facilities.

Upon completion of a site study, the Mean+SD spectrum from that study may be plotted on Figure 9, allowing a comparison of that site with the total population. Alternatively, the data from the 12 sites could be plotted as percentiles of the total population.

6 Conclusion

Ground vibrations measured at a site may vary in frequency, time and space, leading to a fairly complex representation of all the statistical variables. A variety of methodologies have been presented to illustrate how these three variables may be represented graphically, as well as means to compare the statistics of two sites and to compare a given site to a larger population.

7 References

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