The Effects of Ground Vibrations on Nanotechnology Research Facilities

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Abstract— **Nanotechnology has been defined as research and technology development dealing with particles and systems with dimensions of approximately 1 to 100 nanometers. Some aspects of this work require extremely stable environments. Very stringent limits are often placed on vibration amplitudes. In many cases, a vibration environment appropriate for semiconductor production is adequate. In other cases, it may not be stringent enough. In still other cases, it may be too stringent, and expensive vibration controls may not be cost-effective.**

This paper examines the environmental requirements of nanotechnology from the perspective of a member of the advanced technology building design team, the vibration consultant. It explores the variety of vibration environments required by different parts of the nanotechnology community, and how some of the more demanding of these environments are being provided.

A desirable vibration environment at a site may be degraded by groundborne propagation of waves from a variety of sources such as vehicle traffic, rail, central utility plants, construction, and other research facilities. The nature and potential impact of some representative examples are discussed, along with a clarification of the differences between vibration representation for these facilities and that typically used for other civil applications such as blast and construction monitoring.

Keywords—**vibration, site studies, nanotechnology**

INTRODUCTION

The research equipment in use by the developing nanotechnology research and production community is, in some cases, extremely sensitive to the environment in which it operates. Environmental factors can limit the performance of this equipment. Environmental vibration, to which the equipment is exposed via its support structures, is one of these factors. It is important to consider the location of the buildings that will house this equipment, as well as the location of the equipment within the building, especially since there are limits to the degree to which the building or equipment can be isolated from the vibration environment.

Scale of Nanotechnology Equipment Vibration Sensitivity

In spite of the advances made in recent years in the design of equipment structures and in the design and application of vibration isolation systems internal or external to the equipment, certain classes of advanced research tools typically have some degree of sensitivity to the environment. This is often roughly in inverse proportion to the size of the particle, feature, line width, cell, etc. under analysis or production by the equipment [1,2].

The degree of sensitivity of nanotechnology research equipment may be gauged by comparison with more familiar vibration amplitudes. For example, the most demanding metrology equipment specifications may require environmental vibration amplitudes 10 times lower than typical microelectronics (photolithography) production floors, 100 times lower than typical laboratory (400x microscope) floors, and 500 to 1000 times lower than just perceptible vibration that might be experienced, for example, on a suspended office building floor under normal conditions.

Limitations Imposed by Groundborne Vibration

The vibration environments of all potential building sites for advanced technology research are limited to varying degrees by groundborne vibration from a variety of potential sources: microseismic activity, transportation, other nearby facilities containing mechanical equipment, etc.[1]

Groundborne vibration may attenuated to some degree with the use of local isolation at the equipment or by common or special foundations or structural design [3,4]. There are limits to the use of these methods, with constraints imposed by practicality and costs. For example, many nanotechnology research tools already employ active or passive internal isolation systems, which cannot in all

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[1] In addition, the sources within the building itself (mechanical equipment, piping, and ductwork; the activities of people; etc.), as well as the structural design of the building itself, can limit the vibration performance of research areas within the building, however this case is not considered here as the building owner or design team often has more control over these limitations.

cases be supported on a second isolation system without detrimental effects due to the addition of an extra degree of freedom. (There are also known cases where equipment manufacturers will not provide a warranty for use of their equipment on local external isolation systems.) Support of entire buildings on resilient systems is not practical in these cases due to the presence of vibration sources within the building that would tend to excite these into resonance (although it is possible to isolate individual laboratory floors in this manner, as discussed in Ref. [7]). Finally, there are limitations to the amount of groundborne vibration that can be reduced by stiff structures, especially at low frequencies (say, up to 20 Hz), where some equipment is most sensitive to environmental vibration. Due to the complexity of modeling soil-structure interaction, there are limitations in the accuracy to which low frequency attenuation can be predicted, especially when there are time and cost constraints imposed.

In any case, for the purposes of certain types of metrology used in research, it is desirable to have vibration amplitudes be as low as possible. The manufacturer of a particular piece of equipment may represent its environmental requirements at a particular threshold for research at a particular dimension. However, it is often possible and desirable in research situations to exceed these limits if the installation environment allows.

Goals of the Site Vibration Survey

Due to the stringent environmental vibration requirements of nanotechnology research and production, and the limited options for local control of low frequency vibration, site selection is critical. A vibration survey of a potential building site (or, analogously, a potential laboratory within an existing building) is carried out to identify present and future limitations on research due to groundborne vibration. It is to be determined whether the environmental vibration is adequately low for the specific function of the building or research equipment.

VIBRATION CRITERIA

Representation of Vibration Data

The various ways of representing vibrations have been discussed in detail elsewhere [5,6]. What is important to point our here is that the manner in which equipment manufacturers represent the sensitivity of their tools, as well as the format of several families of "generic" criterion curves, may be different from the vibration data representation formats commonly used in the civil engineering discipline (e.g., response spectrum, peak particle velocity, power spectral density, etc.).

Advanced technology research equipment tends to be most sensitive to vibration at one or several critical structural resonances within the tool. For example, these might be associated with the fundamental resonance of a structural element supporting an electron beam source or target, or of an internal isolation system. Thus, it is common practice to express these points of maximum sensitivity as frequency domain spectra in either constant narrow bandwidths (e.g., 1 Hz) or in proportional bandwidths (one-third octave bands). Otherwise, there is very little standardization: equipment manufacturers may express their tool vibration requirements in displacement, velocity, or acceleration in various units, bandwidths, and waveform indices (rms, zero-to-peak, peak-to-peak).

In designing a laboratory or production floor that will contain several or many different research tools, it is necessary to select a design specification that is easily convertible among these various individual equipment environmental requirements (and vice-versa). Furthermore, the format of the selected design criteria must be appropriate to the vibration environment typically found in laboratory buildings or sites. These tend to be relatively steady-state random vibration environments, but often containing "tonal" (single frequency) components associated with rotating machinery.

In summary, the particular representation format of vibration in advanced technology building site selection and design is a consequence of the following considerations:

1) One must be able to convert to it from frequency domain specifications commonly used by equipment manufacturers. Thus, time-domain representations and overall single index representations of amplitude such as peak particle velocity are not practical.

2) The design specification must be able to simply represent groups of equipment with many different resonance frequencies. Thus, use of response spectra would be somewhat cumbersome in this case.

3) The specification should be able to represent both random and periodic (tonal) environments. Spectra expressed in power spectral density (PSD) well represent random vibration, but cannot be used to represent tonal vibration.

Generic Criterion Curves

During the design phase of a nanotechnology building project, it is not uncommon that the specific instruments that will be used are unknown, either because the experimental work processes have not yet been established, or because the building is being designed to accommodate equipment that does not exist. For this reason it is common to select one or several "generic" criterion curves, which are intended to represent entire classes of tools or processes [2]. These curves have been developed based on experience with the requirements of similar equipment, consideration of the scale of analysis coupled with knowledge of typical engineering practice in tool design, the limits of what is achievable for the more stringent curves, and other considerations.

Fig. 1 illustrates several generic criterion curves commonly in use in nanotechnology facility design [7]. These curves are expressed as velocity spectra in one-third octave bands of frequency.

When applied to a site or a particular laboratory floor, the criterion is intended to represent the most stringent equipment requirements on the floor or site area. Thus, a criterion selected for a particular floor may be conservative for the less sensitive equipment used in the same research or process.

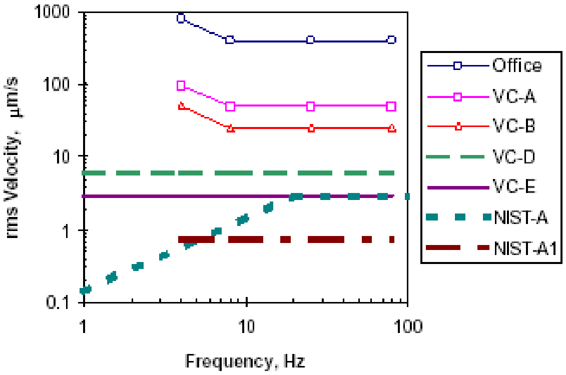

Fig. 1: Common generic vibration criteria in the form of velocity spectra.

Classes of Nanotechnology Research Equipment and Ranges of Sensitivity to Vibration

Although there is considerable variation in the goals, designs, and layout of the various nanotechnology facility projects currently under design or operation, some general classes of research or equipment and typical corresponding vibration sensitivities have been established [7]. These are shown in Table 1. In general, these are only guidelines, which would be verified later (if possible) by comparison with actual equipment requirements. It is important to identify these general relationships early in the design process to provide an efficient and cost-effective design and, as discussed below, so that the most sensitive equipment can be located on the quietest part of the building site.

TABLE 1: GENERIC CRITERIA ASSIGNABLE TO NANOTECHNOLOGY SPACES AND EQUIPMENT

Space or Equipment Type	**Criterion**
Research Offices, Computer Modeling	ISO Office
Generic Laboratory Space, Optical Microscopes, Epitaxy, CVD	VC-A or VC-B
Photolithography, Nanofabrication	VC-D or VC-E
Metrology, Surface Characterization, SEM, SPM, AFM, TEM, FIB	VC-E or NIST-A
Instrument Development	NIST-A1

Reference [7] describes typical structural designs used to achieve these various criteria.

TYPICAL GROUNDBORNE VIBRATION ENVIRONMENTS

"Ambient" Vibration Conditions

The ambient or background vibration condition of a site refers to the typically broadband steady state random vibration environment that is not perturbed by local transient or continuous sources. Here we make a distinction from typically higher induced vibration from local traffic and rail sources, mechanical equipment and nearby facilities, etc. The ambient condition usually represents the best achievable vibration environment on a site, before the addition of access roads and a building with associated vibration sources.

Experience shows that there can be significant variations in the ambient conditions of a site, depending on the soil type, condition, and water content, proximity to "civilization" (distant highways, cities, etc.), and possibly, orientation with respect to other natural sources, such as tidal vibration and local seismic conditions, although impact from these sources may be more subtle or infrequent. Fig. 2 shows vertical vibration velocity spectra on various sites as an illustration of a range of conditions. The range of conditions varies over roughly two orders of magnitude, from a very remote site in the Midwestern USA (site 4) to an undeveloped site in a crowded industrial park in Taiwan (site 3). Another notable feature on some of the particularly "soft" sites with relatively saturated soils (sites 1, 3, 5) is a tendency to have low frequency resonances.

Fig. 3 shows the same data reformatted in one-third octave bands of frequency for comparison with the generic criterion curve VC-E (3.2 µm/s). Some of the sites exceed this criterion, which is often required for metrology at nanometer dimensions, especially at low frequencies. These sites might be rejected for this type of research, or else require mitigation, if possible.

Note that it is difficult to predict or estimate the ambient conditions on a new site from such illustrations of typical conditions. In most cases, a survey of the actual conditions is recommended.

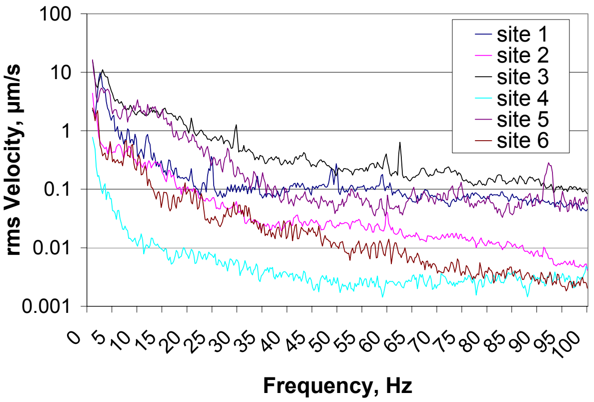

Fig. 2: Typical narrowband (0.375 Hz effective bandwidth) velocity spectra for various undeveloped sites.

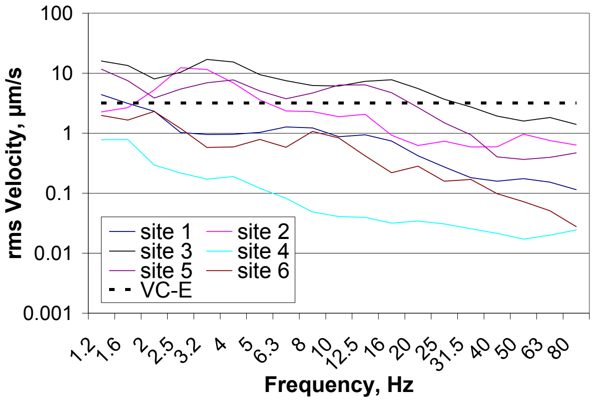

Fig. 3: Data from Fig. 2 reformatted to one-third octave bands of frequency, compared with criterion VC-E.

Vibration due to Rotating Mechanical Sources

Fig. 4 and Fig. 5 show data from undeveloped sites impacted by rotating mechanical equipment located on adjacent sites. In the case of sites 7 and 9 the tonal vibration is associated with a nearby semiconductor plant, in the case of site 8 the vibration is from a printing plant located on the adjacent property. It is often possible to identify and relocate or improve the isolation of certain types of stationary sources (split case pumps, compressors, etc.), assuming the owner is amenable to this. Isolation of other mechanical sources (large reciprocating presses, vertical turbine pumps, non-stationary equipment) may be more difficult.

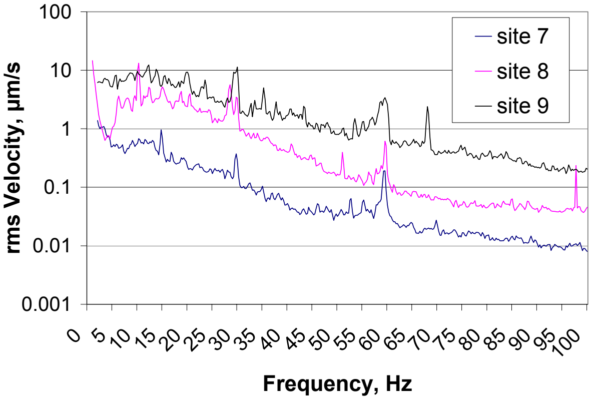

Fig. 4: Typical narrowband (0.375 Hz effective bandwidth) velocity spectra for various undeveloped sites impacted by tonal vibration sources (rotating mechanical equipment).

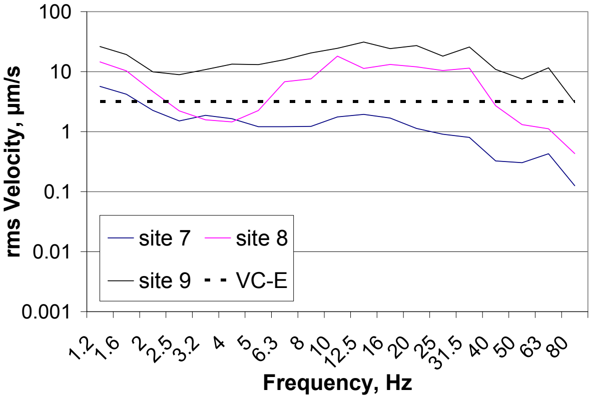

Fig. 5: Data from Fig. 4 reformatted to one-third octave bands of frequency, compared with criterion VC-E.

Vibration due to Vehicular Traffic

Vehicular traffic can pose an even greater impact to sites than ambient conditions, especially in urban and suburban areas or near highways. The impact varies depending on the proximity of the road, the road condition, traffic density, and the vehicle weight and speed [8]. For example, Fig. 6 illustrates impact as a function of vehicle weight. High-speed roadways typically create the greatest impact, but even on-site access roads must be taken into consideration. The impact to a site can be either continuous or transient (or both), depending on the traffic density and mix of vehicles.

The impact force from vehicular traffic tends to be relatively broadband (random), however, with propagation, high frequencies are reduced in amplitude more quickly due to the frequency dependence of the dissipation of energy within the soils (this material damping also occurs, of course, for propagating vibration from the other sources discussed in this report) [9,10]. These effects are illustrated in Fig. 7 and Fig. 8. Once a set of attenuation curves have been developed for a particular site, these data can be used to define setback distances to various vibration sensitive areas.

Although the frequency response and attenuation effects shown are characteristic, the specific values of attenuation with distance and the frequency response are highly specific to the traffic source parameters and soils medium, and thus must be evaluated on a case-by-case basis if a relatively high degree of accuracy is needed.

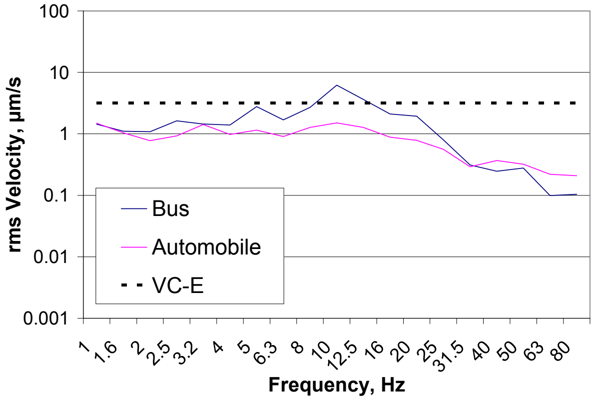

Fig. 6: One-third octave band velocity spectra measured at the same distance from vehicles of different weights traveling at 30 km/h.

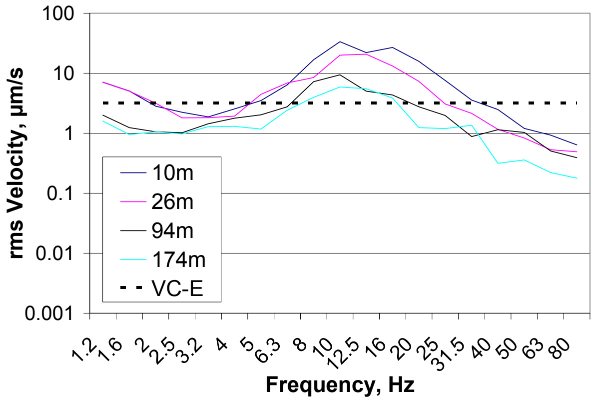

Fig. 7: One-third octave band velocity spectra measured at different distances from buses traveling at 30 km/h.

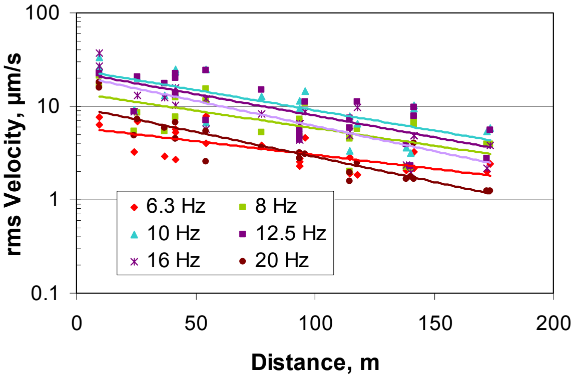

Fig. 8: Attenuation of one-third octave band velocity versus distance from heavy vehicles traveling at 30 km/h.

Vibration due to Rail Traffic

Another potential source of vibration that must be evaluated in site selection is rail vibration. Considerations similar to the evaluation of vehicular traffic should be taken. There are a few differences worth noting, however.

Rail system vibrations vary from the relatively light impact due to slow moving light rail systems, through heavy freight systems, to high-speed rail systems. All of these can impact a site to varying degrees depending on the distance, soil conditions, any track bed isolation systems employed, etc. Light rail systems will tend to have a smaller range of influence, and high-speed rail systems can cause exceedances of some of the more stringent criteria shown in Fig. 1 at distances as far away as 1 km or more, depending on the soil conditions.

Compared with vehicular traffic, the incidence of impact from a rail system may be relatively rare in the case of freight systems. Depending on the research or process to be carried out in the nanotechnology facility, this may or may not reduce the impact from this source. On the other hand, light rail systems tend to have more regular service, potentially impacting a nearby site quite frequently during a 24-hour period. Another consideration is that rail vibration sources are more or less transient, depending on typical train lengths and speed.

It is often possible to provide track bed isolation for rail systems. However, these types of isolation systems typically have resonance frequencies in the 10 to 20 Hz range, at which there may be amplification of the vibration. While these types of isolation systems can be beneficial for controlling rail vibration and noise impact to residential or commercial facilities, they may not be compatible with the vibration requirements of advanced technology facilities.

Construction Vibration

Vibrations due to nearby construction activities can be quite varied, due to the many types of potential activities (excavation, piling and drilling, compacting, etc.) [10,11]. Even though they are typically of a temporary and transient nature, some of these activities can be exceptionally disruptive to low vibration environments. A detailed review of construction vibration sources is outside the scope of this paper, but it is important to point out that the potential for future construction activity near the operating nanotechnology facility must be considered.

CONCLUDING COMMENTS

Several considerations concerning groundborne vibration impact to nanotechnology facilities have been presented. In particular, it is emphasized that siting studies must account for present and future impact from various types of sources near and far from the facility, and that the study should account for the specific (or generic, if necessary) vibration sensitivity of the research to be carried out.

A site vibration evaluation is recommended in any case for facilities requiring the equivalent of generic criterion VC-D or more stringent, and for any facility proposed to be located near possible high vibration sources (railways, industrial facilities, etc.).

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