Construction of Nanotechnology Facilities

Concrete proving the best material for vibration control

BY HAL AMICK AND PAULO J. M. MONTEIRO

The sophisticated working environments required for nanotechnology facilities pose big challenges to their designers and constructors. The environmental requirements of a nanotechnology facility may include temperature and humidity control, air cleanliness, 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 created when working at a small scale. Very few existing buildings can meet these demands—new construction is generally required.

In this article, we will be exploring nanotechnology from the perspective of a member of the advanced technology building design team—the structural dynamicist—and focusing on concrete, often the structural material of choice for these facilities. First, we will show how one application in nanotechnology has led to ongoing research addressing some of concrete's dynamic properties. Then, we will discuss some of the needs for further research in concrete technology.

WHAT IS NANOTECHNOLOGY?

Nanotechnology is generally defined as research and development (R&D) dealing with particles and systems that have dimensions between 1 and 100 nm (1 nm is 10^{-9} [one billionth] m). Although conductors and other features of computer chips have historically been at microscale (10^{-6}), this is changing. For comparison, Fig. 1 provides a basis for comparing scales for natural and manmade objects, with some sizes of features in cement paste that might be more familiar to the reader.

The prefix *nano* may be used to modify three existing terms. Nanoscale implies a size range—dimensions that are on the order of 1 to 100 nm. Nanoscience implies research at nanoscale. Nanotechnology implies implementation and production at nanoscale, which in turn implies a mature nanoscience. We have not yet fully developed nanoscience, so the use of the last term—the most popular one—is premature.

Nanotechnology requires that

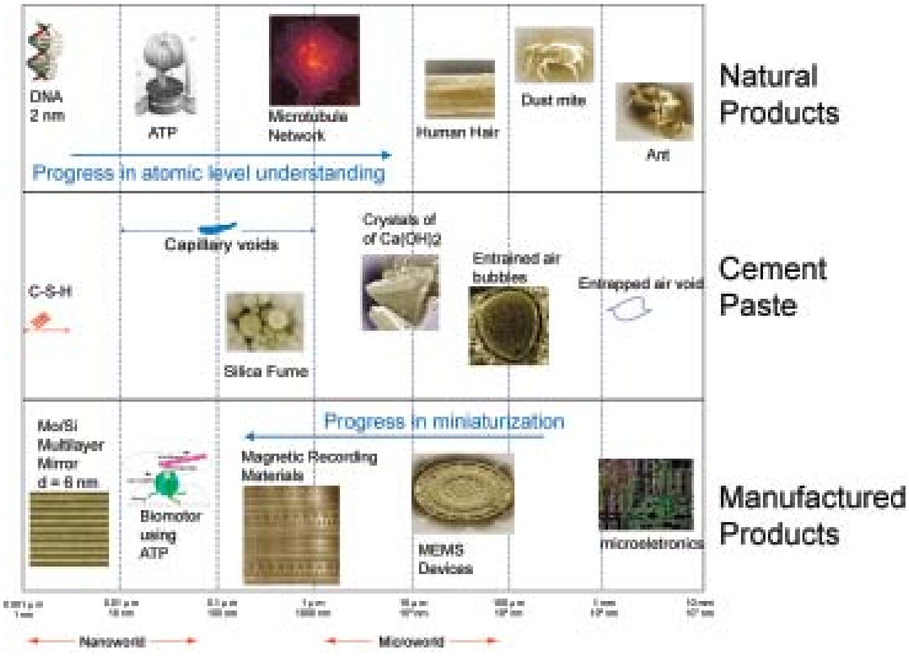


Fig. 1: Comparison of scales of natural and manmade products with those of features in cement paste[1,2]

instruments position a probe within an accuracy of a few nm, measure quantities (such as nN), and fabricate objects perhaps only a few molecules thick and a few nm^2 in area. Therefore, the thermal variations in the room must be small enough that an object does not change its size by more than a few nm or the probe's control system would place the probe at the wrong location. Electromagnetic fields within the structure must be so stable that electrical signals can be measured in terms of nA and nV. Some spaces require acoustics comparable with those of a recording studio. Tiny airborne particles may have dimensions up to the thousands of nm, so contamination control—particulate and chemical—must meet demanding tolerances. Vibrations must be two to three orders of magnitude less than the threshold of perception. All these requirements must be met in a facility with as much as 100 times the power consumption by mechanical systems—and over 50 times the air movement—of a conventional building. These features translate into very demanding building and material specifications that must be prepared by the design team.

At the beginning of 2003, several dedicated nanotechnology facilities were under construction throughout the world or had recently been completed. These include buildings at Cornell and Northwestern universities in the United States and University College, London, UK; a large cleanroom at the National Nanotechnology Development Laboratory in Taiwan; and a somewhat smaller facility at the Naval Research Laboratory in Washington, DC. The construction costs for these facilities range from $12 to $60 million (U.S.).

Minimizing errors in measurement and positioning can become quite critical in nanotechnology, justifying the expenditure of large sums for environmental control. For example, a significant R&D effort was carried out as part of the design of the National Institute of Standards and Technology's (NIST) Advanced Measurement Laboratory, now under construction. One of these investigations explored how off-the-shelf temperature control systems could be used to achieve room thermal control of ±0.01 °C, previously thought to be impossible without an expensive, custom control system.[3] The building costs cited previously seem large when considered in the context of academic or government buildings, but consider that a single semiconductor production facility might have a construction cost on the order of $700 million (U.S.) and have 10,000 to 15,000 m^2 of cleanroom.

LOW-VIBRATION ENVIRONMENTS

There is a growing need for low-vibration environments for these nanotechnology facilities. To some extent, the creation of these spaces is under the purview of a very specialized subset of structural dynamicists. For two decades, the semiconductor industry has been a driving force behind the evolution of design methodologies associated with low-vibration environments. Facilities are placed at sites with low ambient vibrations and are designed very conservatively.

These more stringent requirements cause designers of these spaces to revisit some basic design issues: a quiet site is no longer enough. Figure 2 shows the range of vibrations allowed for these facilities. The threshold of human perception is about 500 μm/s. An office or meeting space may have some perceptible level of vibration; however, most other workspaces in nanotechnology facilities must meet a vibration criterion more stringent than human perception.

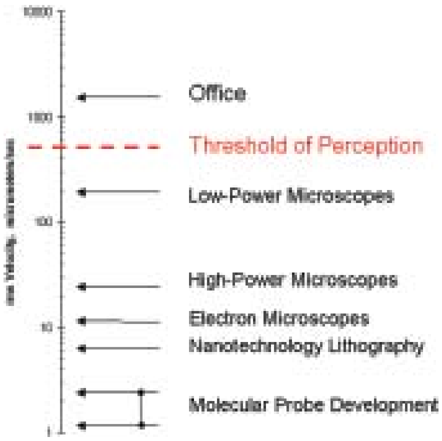
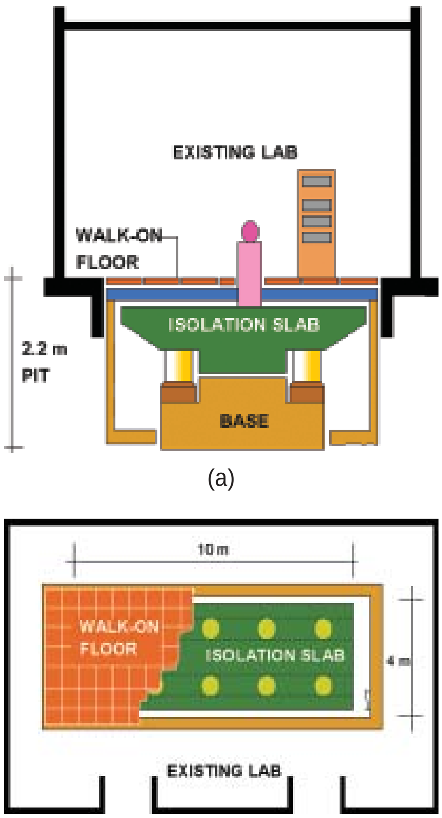


Fig. 2: Vibration criteria of typical advanced technology equipment

Low-power microscopes (40x to 100x) and surgical suites require a level of vibration that is an order of magnitude more sensitive than people can feel. Electron microscopes and semiconductor photolithography necessitate another order of magnitude more sensitive. Much of the equipment associated with nanotechnology is more sensitive still, and the environment required for development of new molecular probes (such as those used for atomic force microscopes and other forms of probe microscopy) is even more stringent.

Typically, the best sites have vibration amplitudes in the range of 3 to 6 mm/s. Some nanotechnology processes require vibration amplitudes of 1 μm/s or less, requiring extra measures for even the quietest sites.

Concrete is the material of choice for many critical structural components in advanced technology facilities. Most vibration-critical areas are placed in slab-on-ground locations, with slabs much thicker than usual (200 to 600 mm). Cleanroom spaces requiring a basement are often placed on deep waffle slab systems 700 to 1200 mm deep, depending on the column spacing. General laboratories in the upper levels of these buildings—often intended to meet the needs of microscopes—are designed with



(a)

(b)

Fig. 3: Conceptual section and plan views of NIST-A1 isolation system[4]

either one-way slab or composite steel/concrete framing, though the depths are greater and the spans are much shorter than found in conventional structures.

A relatively new application for concrete is in spaces with the most demanding vibration requirements. These vibration needs may be met by a combination of a quiet site and pneumatic isolation using air springs. In the past, this isolation was achieved by commercially available optical benches supported on legs containing air springs; however, this is not an all-purpose solution. Some applications require a very long optical path, and multiple optical tables might lead to beam misalignment. Other applications may require the working surface in the lab to be at floor level, necessitating a pit for the isolation unit. Some structures require an extraordinarily large isolated mass to improve the performance of additional stages of isolation or to lower the center of gravity of the structure.

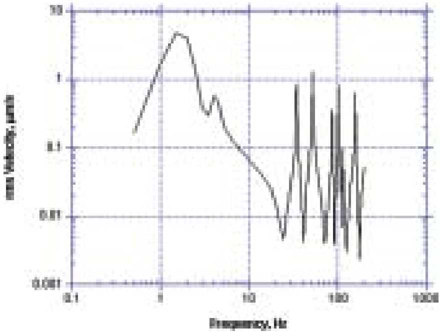


Fig. 4: Velocity spectrum resulting from hammerblow, measured at center of prototype NIST-A1 slab[4]

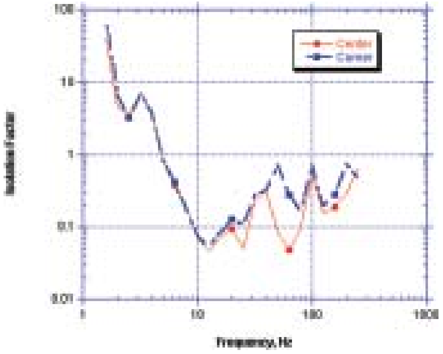


Fig. 5: SRSS representation of isolation system performance at the center and corner of the slab[4]

Several R&D lab designs have employed large inertia masses supported on huge air springs, such as the system shown conceptually in Fig 3. This configuration is becoming known in nanotechnology circles as a NIST-A1 slab, denoting the vibration criterion it was intended to meet for NIST's Advanced Measurement Laboratory. (A more generic term is "keel-slab.") A 4 x 10 m prototype was designed and built in one of the existing labs at NIST and is now used to support development of a force measurement system capable of measuring nN, one of the metrology requirements of nanotechnology.[4]

When struck with a hammer, the prototype keel-slab produces a velocity spectrum similar to that shown in Fig. 4, the exact shape of which depends upon excitation and measurement locations. The broad hump at low frequencies represents the highly damped response of the air spring suspension system. The sharper peaks at frequencies between 34 and 120 Hz represent the first five internal bending and torsional resonance frequencies of the large concrete mass. These peaks are much sharper than those of the air springs, indicating much lower modal damping of the concrete.

Figure 5 is a representation of the vibration isolation capability of this slab at a particular bandwidth associated with NIST's vibration requirements. The isolation becomes quite good above 8 Hz but degrades at frequencies above 30 Hz due to the presence of amplification associated with the internal resonances of the concrete mass. At some frequencies, the effect of the isolation is completely cancelled.

In the design of NIST's new laboratory, designers avoided this problem by limiting the geometry of the isolation mass. None of the dozen slabs installed had dimensions exceeding 4 m, which forced the fundamental bending resonance to lie well above 100 Hz—the researchers' frequency range of concern. Circumstances may arise, however, in which a larger system—similar to the prototype—might be required.

It can be shown that if the concrete's material damping could be increased from a nominal 0.2% to, say, 2%, the isolation performance at the internal resonance frequencies could be improved tenfold. Higher damping might improve that performance even further. This would mean that room-sized isolation systems might provide adequate isolation over a significant frequency range.

In addition to keel-slab isolation systems, the capability to increase concrete's damping as a part of the design process might lead to better attenuation of structure-borne vibrations in advanced technology buildings. These two benefits alone have justified a much closer examination of the variables that control concrete damping.

DAMPING AND CONCRETE

A structural engineer generally has a good understanding of the roles that structural stiffness and mass play in dynamic response. Resonance frequencies are functions of stiffness divided by mass (increasing the mass decreases the resonance frequency). At frequencies less than the fundamental resonance frequency, the dynamic response of the structure is controlled by its stiffness. At frequencies higher than the fundamental resonance frequency, the dynamic response of the structure is controlled more by its mass than by its stiffness.

For response at frequencies at or near the resonance frequency, damping becomes the most important structural property. When excited at the resonance frequency, the response of a structure is kept within the bounds required by nanotechnology by damping. In fact, the amplitude of the vibration is inversely proportional to the damping of the structure, and the amplitude of a response spectrum for any given earthquake is reduced as the damping ability of a structure is increased.[5]

Damping, as compared with modulus of elasticity or density, is the least understood of structural material properties. In general, the structural engineer assumes the damping of a concrete structure based on the behavior of a structure with a similar structural configuration. Unlike the elastic modulus of concrete, which the designer can basically specify by choosing a compressive strength or its density—which can be controlled with judicious aggregate selection—"it is not possible to analytically determine the overall damping for a structure."[6]

Most often, the goal when designing the structural elements to resist dynamic forces in advanced technology buildings is to minimize structural vibration amplification between two points in a structure. This usually requires that the designer create members with resonance frequencies that are as high as practical, conceptually calling for a light, stiff structure. The damping of that structure, in general, is accepted as is, and one assumes that the high resonance frequency members will shift the amplification to a frequency where the vibrations are of lesser concern.

In the case of the isolation system discussed previously, the amplification is occurring between the tops of the air springs and the top surface of the isolation system. Until damping can be increased deliberately, the only option available to the designer is to achieve a higher resonance frequency, which limits useable surface area.

The best material for many structural dynamics settings in high-tech buildings is one with a high modulus of elasticity and damping, and low density. Compressive strength alone is not of major importance. Further research should be conducted to better quantify many of the assumptions currently inherent in designing advanced technology structures.

The damping property of concrete has been studied since the 1930s, but virtually all of the research has focused on identifying the microstructural mechanisms in concrete that cause damping. Very little attention has been given to developing means by which damping could deliberately be modified, placing it under the control of the structural dynamicist much like compressive strength and modulus of elasticity. Research is underway at the University of California, Berkeley, to develop such tools for the designer. Parameters being investigated include admixtures, variations in water-cement ratio (w/c), alterations of aggregate, and modifications of reinforcement. The objective is to provide the designer with a toolbox of methods by which damping may be increased to, say, 2%, or perhaps as much as 10%, and document the effects of these methods on other important parameters such as strength, modulus of elasticity, and durability.

There are several viable methods to modify damping for this designer's toolbox. For instance, a designer already has a polymer admixture available consisting of styrene-butadiene latex and a vegetable gum, but its effects on the other concrete properties are not yet thoroughly documented.[7] This polymer admixture can increase damping from concrete's nominal value between 0.5 and 1.0% to about 2.5%. Other polymer admixtures may also improve damping. A second line of thought involves practices we've been taught to consider undesirable.

For example, prior research has established that concrete damping is partially due to the presence of microfractures in the concrete matrix. Would deliberately increasing the level of microfractures (by increasing the w/c) increase the damping? A third option involves technology quite popular in aerospace structures: constrained-layer damping. This practice might only modify the damping of particular modeshapes, rather than across a wide range of frequencies and deformed shapes, but in some instances this may be desirable.

The evolution of advanced technology facilities, particularly those for nanotechnology, will require a broad effort from a variety of building technologists to meet the sophisticated performance requirements of tomorrow's R&D and production. Though often perceived as “low tech,” concrete will play a key role. Much work remains, but concrete might become the structural dynamicist’s material of choice.

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Selected for reader interest by the editors.

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