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Nanotechnology research facility - a vibration and noise control design case study

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Abstract

A nanotechnology and molecular research facility was proposed. Vibration and noise control would be critical to the facility's success. Roadway traffic, a nearby power generation plant and buildings in the vicinity were potential sources of ground borne vibration disturbances. Mechanical equipment, user-installed support apparata and occupant activities were potential sources of internally generated vibration disturbances. On-site ground borne vibration was measured for comparison with generic floor vibration to qualify the site. Results were analyzed relative to sensitive equipment vibration tolerance, perception by occupants, audible radiated structure borne noise in acoustically sensitive spaces and resolution-degrading motion for scanning and for transmission electron microscopes or other nanotechnology clean room equipment. Design guidelines and structural vibration control concepts were recommended to the structural engineers, including de-tuning, damping and isolation. Recommendations were provided for mechanical noise control and vibration isolation. Architectural noise control, sound isolation and room acoustics guidelines were provided for research, office and meeting spaces.

This case study discusses the desired vibration and noise control objectives and the design solutions that were implemented. Building photographs are presented. Pre-construction conditions are graphically compared with post-construction measurement results to demonstrate apparent degree of success in mitigating vibration.

1 Introduction

1.1 Proposed Building

A nanotechnology research facility was proposed on a large university campus. The facility would incorporate research laboratories and support spaces, clean rooms, faculty and research offices with conference spaces, core and building systems spaces. The clean rooms and laboratories would house vibration sensitive research equipment. This case study presents the existing site conditions, design parameters, vibration criteria, recommended vibration control concepts and results. Criteria for airborne noise spectra were established, including low frequency sound that could induce vibration into lightweight structures, but noise is not discussed in this case study. In addition to vibration control design recommendations, ground borne and structure borne vibration spectra are presented in this study and compared with criteria for *i*) pre-construction, *ii*) substantial completion of construction and *iii*) post-occupancy conditions to demonstrate results.

The site is a gradually sloping area of a large campus with many surrounding academic teaching and research buildings. Layered limestone and fractured limestone is common at shallow depths below the soil surface. An existing science building was initially considered for renovation, but proved difficult to effectively convert for due to the unique requirements for building systems and clean room support. A building addition was then proposed with separate foundation and linked to the older building, but with no significant structural ties. This provided an opportunity to design for specific conditions without the constraints of adapting existing conditions. Limited available space on the site caused the nano-science facility to be designed with a narrow footprint and several floors.

Ground borne vibration sources that contribute to ambient conditions on the site include moderate roadway traffic, vibrations from other buildings and vibrations from university central utilities, including large cooling towers and turbine generators one block from the site. Steam, chilled water and other utilities are piped via underground tunnels in lieu of central plant equipment in buildings.

More nano-science research center information may be found on their site: http://www.cnm.utexas.edu/facility.html

1.2 Building Vibration Criteria

Laboratory/research floor criteria were recommended by the laboratory consultant with concurrence by this vibration consultant to not exceed VC-A (Fig. 1), 50 µm/sec RMS velocity from 1 Hz to 100 Hz, to be applied generally for floors in research spaces. Individual research and clean room equipment with less vibration tolerance, i.e., requiring more stringent criteria, would be treated individually to achieve their manufacturers' criteria. More liberal criteria were permitted for office and support facilities.

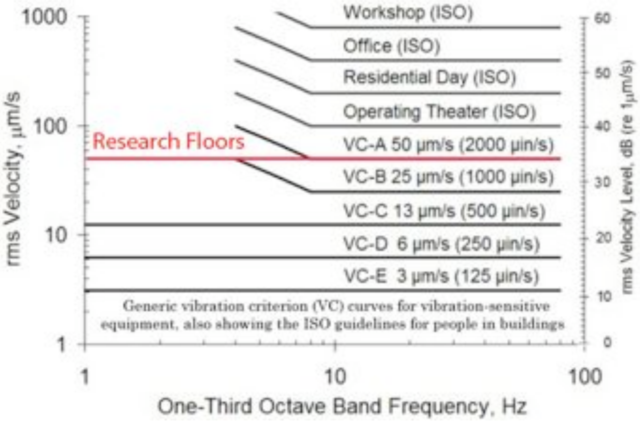

Fig. 1. Generic Floor Vibration Criteria [1]

2 Building Site Conditions

2.1 Ground Borne Vibration

Measurements of ground borne vibration were conducted at three building site locations on surfaces that appeared to have good coupling to the ground. Measurements for use in determining spectra and levels of vibration relative to the building floor vibration criteria were made in three mutually perpendicular axes; x, y and z, in ¾ Hz and in 1/3 octave bandwidths, from 1 Hz to 300 Hz. A Larson-Davis 2900 2-channel spectrum analyzer was used with Wilcoxon 731-A seismic (10 v/g sensitivity) acceleration transducers. Acceleration (db re: 1 g rms) data was converted to velocity for comparison with generic floor vibration criteria.

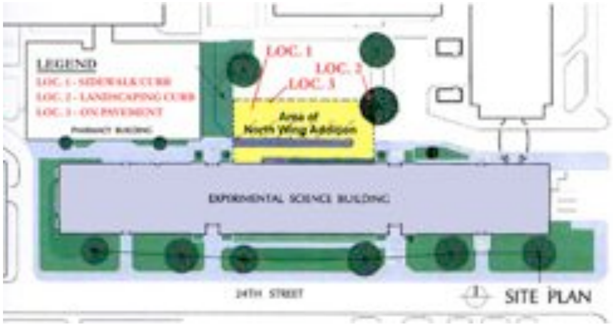

Fig. 2. Site Plan with Measurement Locations.

Spectral results were determined in each directional axis for integrated average, Leq, and for maximum transient, Lmax. Only maximum levels for vertical vibration, typically greater than horizontal directions, are displayed here, although all axes were evaluated and considered in design.

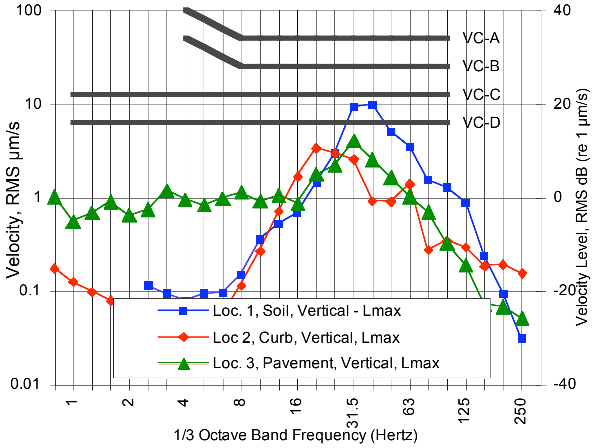

Fig. 3A. 1/3 Octave Ground Borne Vibration at Site [2]

Soil dominant frequencies are typically in the 5 Hz-17 Hz range [3] (we are reluctant to refer to resonant frequencies for non-homogeneous soils). Low amplitude ground borne 1/3 octave vibration levels were noted from 1 Hz to 16 Hz. 1/3 octave amplitudes were greatest in the 20 Hz-40 Hz range, but below VC-A building criteria.

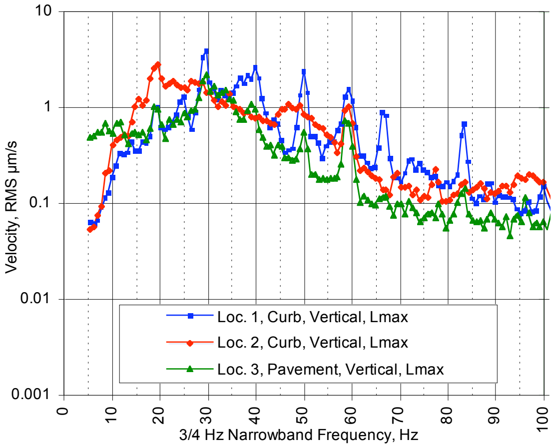

Fig. 3B. Narrow Band Ground Borne Vibration at Site

The North American electrical power frequency is 60 Hz. Electrical sources have prominent 30, 60, 120 and 240 Hz tonal peaks (re: fundamental and harmonic frequencies). Consequently many motors operate at nominal 1800 or 3600 rpm with 30 and 60 Hz disturbing frequencies.

$$F_d = rpm / 60\ sec \tag{1}$$

Actual rotation rates, near 1750 and 3550 rpm are equivalent to 29.2 and 59.2 Hz, respectively. Narrow band spectra indicated peaks at 29-30 Hz and 59-60 Hz, indicating the power generators and other motors in the vicinity. Other prominent narrow band frequencies included 20, 40 and 50 Hz.

3 Analysis and Recommendations

Pre-design measurements of ground borne vibration levels revealed greatest amplitudes at frequencies near 30 Hz, but they were not excessive relative to allowable VC-A floor vibration criteria. When completed, the facility would have building equipment, such as fans and pumps driven by electrical motors with peak disturbing frequencies of 29 Hz and 59 Hz. Therefore, it would be desirable to "de-tune" the building structure from elements that could contribute mechanical vibrations at the greatest ground frequencies.

Recommendations were made to de-tune the structure from ground frequencies to avoid resonant or harmonic frequencies coincident with external prominent ground or with internal building equipment disturbing frequencies. Recommendations were made to avoid 7-8 Hz or 14-16 Hz resonant structure frequencies, because harmonics would match 28-32 Hz ground and equipment frequencies. [4]

3.1 Source-Path-Receiver

Research laboratory spaces were programmed with low permissible floor vibration, re: VC-A. Support spaces, which might house ancillary equipment, specimen preparation or research offices, did not need the same amount of vibration control. Building systems equipment would be the primary sources of continuous vibration. Occupant activity, including footfall and rolling traffic in corridors would be sources of transient vibration. User-installed or ancillary research equipment could also be sources of continuous and transient vibration disturbances.

Physical separation of vibration sources and receivers by distance or on different structural bays is desirable to reduce disturbance. Structure borne vibration can transmit over several bays with little attenuation, however; so alternative vibration control methods should be considered at vibration sources, along paths of transmission and at locations of sensitive receivers.

Various types of vibration sources were evaluated for frequency and amplitude characteristics. Where attenuation was determined to be necessary, the choices included a) attenuation, b) damping and c) isolation, either at the source, or along the paths to sensitive receivers. There might also be cases where disturbing frequencies of sources should be changed by speeding or slowing rotation rates to avoid coincidence with building resonant frequencies.

Vibration could be transmitted from bay-to-bay or from floor-to-floor by the building columns, beams and slabs, or by building systems pipes, ducts and conduits. Along these paths of transmission vibration isolation or damping could be considered to attenuate vibration at receiver locations.

3.2 Building Layout

Vibration sensitive and non-sensitive functional spaces were clearly defined. Separation was recommended between vibration sources and sensitive receiver spaces. After extensive laboratory planning, architectural programming and engineering evaluations, the building design was zoned for separate research and support areas to segregate sensitive receivers from vibration sources. The nano-science building addition would be separated from the existing building by vertical building systems shafts. Other core facilities, support spaces and offices would be separated from sensitive research spaces by a central corridor. This physical separation prevented sources and receivers from sharing structural bays (Fig. 4 below).

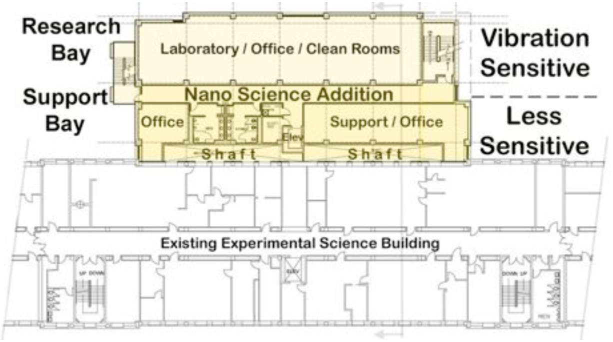

Fig. 4A. Plan: Nano Science Addition to Existing Building Showing Separation Between Research and Support Bays.

Floor resonant frequency is a function of stiffness. For a given structural section, if all else is equal, different span lengths will have the different resonant frequencies.[5] Therefore structural de-tuning could be accomplished between research and support bays by varying span lengths. In addition, zoning the bays as either research or support would create separation.

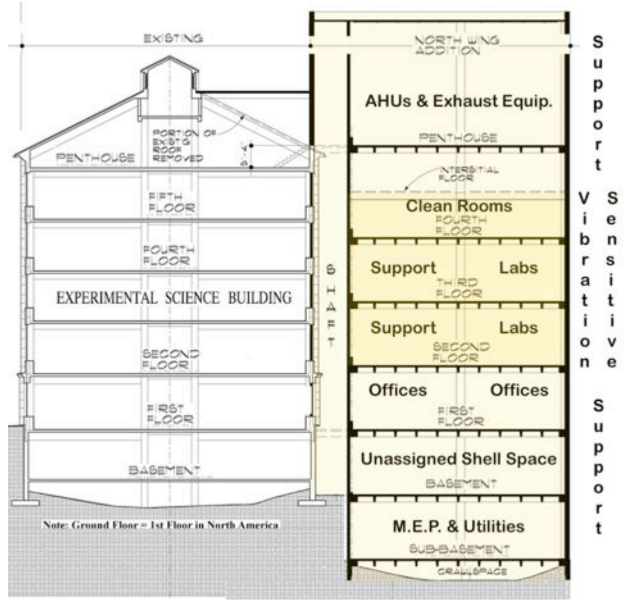

Fig. 4B. Section: Nano Science Addition to Existing Building. Research Floors are Separated from Building Systems.

De-tuning concepts were also applied to separate research floors at mid-levels from offices on the floor below, building systems equipment in the sub-basement and air handling in the penthouse (Fig. 5 above).

3.3 Refinements and Recommendations

Based on the separation and varied span length concepts discussed before, a reinforced concrete pan-joist structure was designed with slightly different resonant frequencies for lab and support spaces (re: span lengths). Additional differentiation was recommended between floors:

- The sub-basement floor, originally designed to be suspended over a crawl space, was altered to slab-on-grade for the main mechanical and electrical equipment rooms with perimeter structural isolation break (SIB) to prevent transfer of vibration to other structural elements.

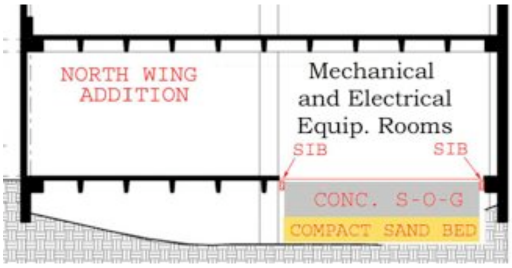

Fig. 5. Section: Isolated Sub-Basement Floor

- For suspended slabs, detuning was recommended by creating a hierarchy of resonant frequencies. Within a range of frequencies from 9 Hz – 13 Hz (to avoid 29-30 Hz coincidence), design the lab and clean room floors for highest frequency, nominally 12 Hz. Design office / support floors to be 10-11 Hz. Design sub-basement and penthouse floors for 9-10 Hz.

Vibration isolation was recommended for building systems according to accepted practices for low-vibration facilities. In addition, the following concepts were recommended:

- Suspend vibration-isolated pipe racks for steam, pumped water; chilled supply and return, ultra-pure, etc., compressed air and other pipes carrying pumped fluids. Place all pipes in sub basement on stanchion supports on the isolated slab-on-grade (re: SIB), on the spring-isolated racks or on individual spring isolated hangers.

Fig. 6. Vibration Isolated Pipe Racks.

- Pipes in the penthouse were recommended either to be on vibration isolated floor stanchion supports or on hangers from the roof structure. Pipe hangers from the roof did not require isolators, because the roof structure was to be structural metal in lieu of reinforced concrete and have different vibration characteristics, i.e. be de-tuned from building columns and floor beams.

- Install flexible connections in horizontal pipe, conduit and duct runs at locations between the support and research bays to reduce transfer from support bay to research bay.
- Install pipe, conduit and duct risers with vibration isolated supports at shafts and floor penetrations. The primary purpose of this recommendation was to prevent transmission of disturbances on any floor to other floors above or below via conduits, pipes or ducts. Vibration in pipes and conduits due to connected equipment was secondary to separation of floors that support pipes.

Structural, electrical, mechanical and plumbing engineers eventually implemented the vibration consultant's recommendations, but not before many discussions about relative merit or need for the extra measures. It was difficult for mechanical engineers to recognize the floor-to-floor transmission of structural vibration via pipe risers, because they were focused on controlling pump vibrations in fluid-bearing pipes. They also questioned why pipes should be isolated, when building columns also transmit vibration vertically. The consultant argued that columns are founded on piers, and connected to a network of stiff beams, while the pipe and conduit risers are connected only to floor slabs, generally near mid-span where the structure is more subject to dynamic deflections.

3.4 Substantial Completion Performance

When the building was substantially complete with building systems operating, but prior to installation of research equipment or furnishings, vibration measurements were made at similar locations on each floor. Measurements were conducted in x, y and z coordinate directions. Only vertical maximum transient measurement spectra, Lmax, are presented here. Horizontal vibration amplitudes were generally less than the vertical at any given location, and all horizontal measurements complied with building criteria.

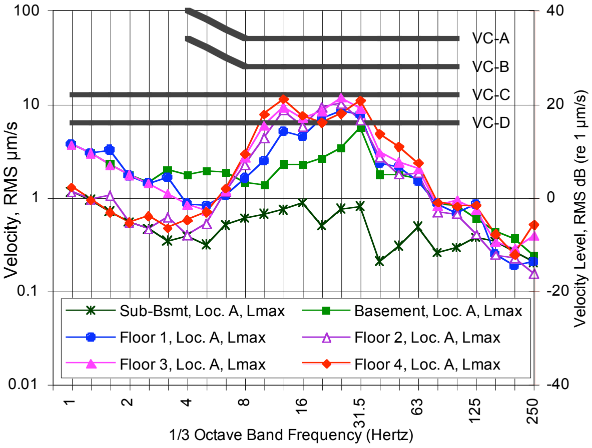

Fig. 7. Substantial Completion Floor Vibration Comparison on Various Floors. [6]

The sub-basement isolated slab-on grade, with inherent damping of the contact with soil [7], exhibited lowest levels, even with mechanical, electrical and elevator equipment rooms. The suspended slabs above, with only minimal damping from to partitions and laboratory casework, exhibited greater vibration levels. With no ancillary research equipment installed and no occupant activities, there was less input energy from vibration sources to disturb floors than was anticipated in the future occupied and fully functional building.

3.5 Post-Occupancy Performance

After occupying the facility, the occupants were generally satisfied with vibration performance of the building relative to programming and performance requirements. The building was designed to segregate research laboratories on 2nd and 3rd floors and to place all nanotechnology clean rooms on 4th floor. Management and administrative offices and a large conference facility were located on the 1st floor. The basement remained as unoccupied and unassigned shell space. The management, planning for future expansion, requested evaluation of the basement floors for possible research equipment installations, even though the structure was not specifically designed to restrain vibration for that type of sensitive occupancy. In addition, the basement floor was located immediately above the building systems mechanical and electrical equipment rooms. The mechanical and electrical rooms are on isolated slab-on-grade, and the major piping and conduits in the sub-basement are vibration isolated.

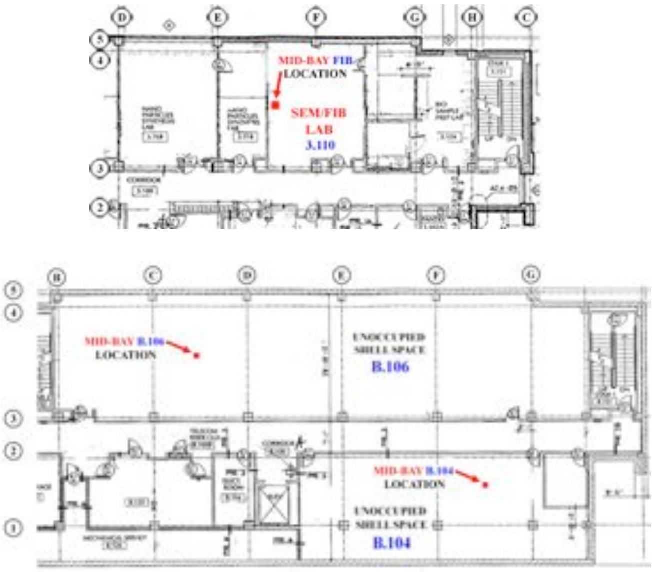

Fig. 8 A & B. Basement and 3rd Floor Lab Plans with Post-Occupancy Measurement Locations.

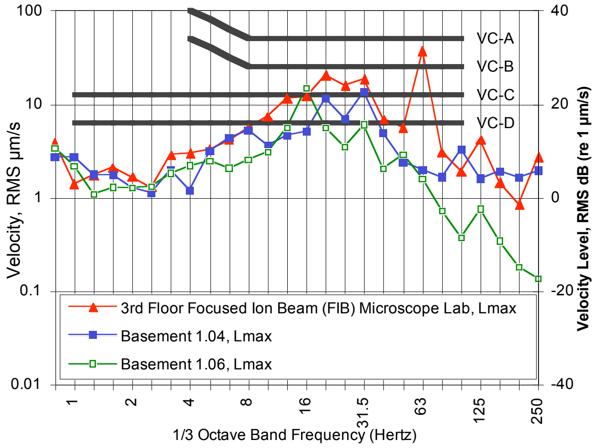

Fig. 9A. Comparison of Post-Occupancy Vertical Vibration Unoccupied Basement vs. Occupied FIB Lab Floors. [8]

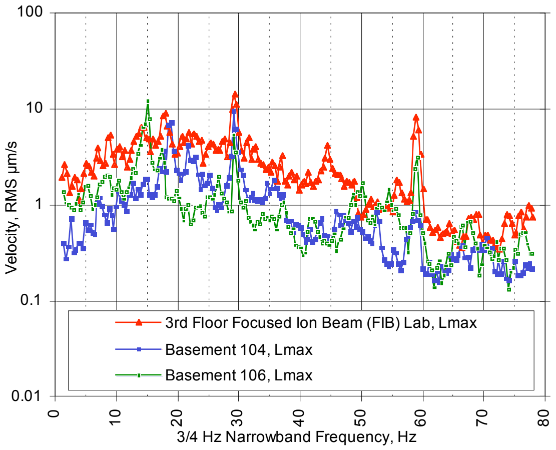

Fig. 9B. Comparison of Vertical Vibration Between Unoccupied Basement and Occupied FIB Lab Floors.

Measurements were conducted at mid-bay locations in two unoccupied spaces, one on the research zone (bay that accommodates laboratories in upper floors) and one on the support zone (bay that accommodates upper floor support spaces). For comparison, an occupied and active 3rd floor research laboratory floor was measured. It should be noted that the focused ion beam (FIB) lab has ancillary equipment, which contributes, to the ambient floor vibration level (59 Hz narrowband, 63 Hz 1/3 octave spike). Researchers' activities within the space also add transient vibrations. Unoccupied basement floors, by comparison, are excited primarily by building ambient vibration from external sources and building systems equipment.

4 Conclusion

The nano-science research facility at The University of Texas at Austin houses many laboratories and clean rooms for nano fabrication and characterization, microelectronics electron microscopes and other vibration sensitive installations. In addition to normal structural design and building systems vibration isolation techniques, special measures were implemented for physical segregation f sources and receivers, structural de-tuning and vibration isolation of elements capable of transmitting floor disturbances to other areas. Local ambient vibrations are not increased by additions from remote sources, resulting in more consistent ambient vibration, relatively free of significant transient disturbances. Measurements at substantial completion demonstrated that the primary 2000 µm/sec rms velocity criterion was achieved in all research spaces. Post-occupancy measurements showed that even the floor immediately above concentrated mechanical and electrical plant installations appears capable of accepting vibration sensitive installations in the future.

Acknowledgments

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Fig. 10. Nano-Science and Technology Building.

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