Noise and Vibration Issues in Contemporary Medical Facilities

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ABSTRACT
Contemporary medical facilities must accommodate the needs of humans and medical instruments or equipment, whether they are for diagnosis, treatment or research. With regard to acoustics, the disparate requirements vary from acoustic privacy to freedom from intrusive noise, to vibration control. Medical facilities also grow and change, subjecting occupants to demolition and construction disturbances. This paper presents interesting problems and conditions that occur in healthcare and research facilities with brief case studies to illustrate them, including construction disturbances, application of criteria, tonal noise effects on patients, and vibration and low frequency noise effects on medical equipment. Measurement data will contrast ambient versus disturbed conditions. Solution concepts to example problems will be presented with photo or drawing illustrations. Discussion will include typical conflicts, constraints, limitations and compromises.

1. INTRODUCTION
Modern health care and research facilities have many diverse noise sources and sensitive receivers. Many sources are also receivers and vice versa; from MRI images that may be distorted by floor vibration to noise in adjacent rooms caused by the MRI magnet, and from human occupants that may be annoyed by noise to human footfall impacts that may disturb vibration sensitive microscopes and instruments. Noise and vibration are closely related. Neither should be considered in a vacuum. Case studies presented below illustrate the links between vibration and noise, and show how practical applications of common-sense vibration and noise control measures can solve problems in medical healthcare and research environments.

2. CASE STUDY: DEMOLITION AND CONSTRUCTION NOISE
Architectural master planning was being done for a proposed expansion of a neonatal intensive care unit (NICU). The expansion would include relocation and construction in phases over a period of years, with demolition and construction taking place within the existing hospital facility to accommodate the moves. The hospital (owner) and architect (client) needed to know what types of noise intrusions might be expected, and how they could be mitigated within the NICU. Based on prior experience, the consultant anticipated both continuous and transient noise disturbances, which could be transmitted by airborne and structure borne paths. For planning purposes, potential noise level estimates were needed to develop isolation, attenuation or mitigation measures. A site visit was made to conduct observations of existing conditions with
measurement of ambient and simulated demolition/construction conditions. Results were to be compared with allowable noise criteria and also used as basis for construction noise estimates.

Acoustical criteria for NICU’s are established for the continuous allowable background noise due to building equipment in unoccupied spaces (re: ASHRAE) and for operations in the occupied and staffed facility (re: Consensus Conference on Newborn ICU Design, Standard 23). Practical application of these standards and methods of implementation were discussed in a Journal of Perinatology 2000 supplement\(^1\) and other Philbin papers. The difference between building background and operational criteria represents the tolerance for transient noise over the continuous background. NC-30 background criterion is equivalent to 39-40 dBA. Standard 23 permits LeqA 50, or an integrated average about 10 dB greater than the continuous background for speech, activity and other transients. \(L_{10}\), the sound level no more than 10% of the time is permitted up to 55dBA, and the instantaneous maximum is permitted up to 70 dBA. For this project the Leq criterion is employed for partition and ceiling re-radiation of structure borne vibration from nearby demolition and construction areas, based on the assumption that typical construction noise events might exceed 10% of time.

![Figure 1: Rotary Drill Hammer and Sledge Hammer](image)

**Figure 1:** Rotary Drill Hammer and Sledge Hammer

**Figure 2:** Two examples of noise and vibration spectrum analysis; on left as level vs. frequency, and on right with vibration amplitude vs. resultant airborne noise spectrum\(^2\). Note frequency correlations between vibration and sound.

Impacts from sledge hammer (manual), jackhammer (power) and large rotary drill (power) were measured at a single location in the NICU from operations on adjacent structures in two different directions (at a distance of two structural bays), to determine relative levels. In one direction the structural slab was continuous along the path. In the other direction, there was a building joint to break the path, but other building elements, such as pipes and conduits provide some flanking. Vibration spectra were measured on the concrete floor slab and on a drywall.
The airborne ambient sound spectrum was measured in the NICU near cribs (more than 2 m (6 ft) from radiating or reflecting partition surfaces) in Leq terms. The disturbance levels of prominent narrow bandwidth peaks were compared with ambient or undisturbed vibration sound levels to determine the different individual construction tool contributions to perceptible noise in the NICU. Multiple source addition was used to estimate potential noise from simultaneous tool use.

Airborne noise and structure borne vibration from demolition were determined to be excessive relative to NICU acoustical standards. Recommendations were developed for the master-planning, to be implemented in design, where appropriate to control noise transmission, and by construction managers to minimize and contain noise within the construction zones:

- Frame temporary and permanent partitions with resilient damping gasket below studs and with resilient channels for drywall. Provide resilient hangers for suspended ceilings.
- Insert (duct) attenuators in supply and return duct penetrations through partitions to reduce break-in and break-out of construction noise via sheet metal ducts and return air transfers. Seal duct, pipe, conduit and other penetrations air-tight with acoustical sealant or fire caulk.
- Insert flexible couplings in pipes, ducts and conduits for structure borne vibration.
- Recess elevation of new floor structures to accommodate resilient underlayments in slabs.
- Erect temporary drywall partition at edge of construction zone to supplement nearby new and existing permanent partitions, which are designed and constructed only for “normal” noise (to avoid building more expensive partition than necessary for construction noise).
- Identify structural discontinuities that can reduce structure borne vibration transfer. Plan for and assure construction phase resilient support or flexible connections in all pipes, conduits, ducts and structural elements that cross or bridge the building structural joints.
- Segregate noisy construction and fabrication procedures, especially those with impacts, outside the building, or provide shop booths or enclosures on-site for noisy procedures. Provide vibration isolation pads under floor of shop enclosures to limit vibration transmission to building.

This will be an on-going project over the next several years, so no performance validation measures are yet feasible. Phoenix Children’s Hospital, the institutional owner and The Stein-Cox Group, Architects, have adopted the recommendations.

3. CASE STUDY: TONALITY AND ANNOYANCE IN PATIENT ROOMS

As part of a hospital renovation and expansion, medical vacuum and medical compressed air pumps were relocated from a basement central plant to an 8th floor penthouse mechanical equipment room (MER). The compressed air inlet was located within the MER, but the vacuum waste-air is discharged to the outside. Previously the waste-air was discharged near ground level toward a busy urban street. After pump relocation, the discharge was at penthouse level across a relatively quiet courtyard from a patient room tower. Complaints began almost immediately after the relocated pump installation was restarted.

On-site observations and measurements of airborne noise and vibration revealed several conditions, the most important being a continuous strong narrow-band tonal peak at 2963 Hz, based on side band frequencies more than 6 dB below tonal peak. Not only was the prominent discrete frequency evident on the vibration spectra of MER floor and vacuum pump equipment, but it was also noticeable in the airborne noise spectrum near the discharge pipe terminus. Sound and vibration measurements were conducted in a 17th floor patient room of the adjacent building. The tone was not apparent in the window or wall surface vibration, but it was clearly audible within the room, and evident on the noise spectrum.
Five pumps were mounted in a common base and frame installation. Each pump’s discharge was connected into a common header pipe, which was routed to the exterior wall.

Each pump was a turbine with 50 blades rotating at 3555 rpm. The blade passage frequency (BPF) of a fan, impeller or turbine wheel is the number of blades passing a point per second. BPF (Hz) is calculated with shaft rotation rate ($R$) in rpm and the number of blades ($N$):

$$BPF = \frac{R}{60} \times N.$$  \hspace{1cm} (1)

In this case, the blade passage frequency equaled the audible tone. Elimination or correction of the blade passage frequency (fundamental solution) would be difficult, and require modification of the vacuum pumps. Attenuation of the prominent audible tone (treatment of symptom) would be relatively easy with only moderate expense, so it was selected as the preferred solution. As the primary solution, mufflers or silencers were proposed for the individual pump discharges or in the header pipe, to attenuate outside airborne noise. The secondary solution efforts employed vibration isolation improvement for pumps and pipes in the MER, to reduce structure borne noise within the building below the MER.

Selection of the mufflers was based on reducing noise in the tonal frequency range only, since the tonal sound, not the broadband noise is the source of the problem. Pipe mufflers are generally of two generic types; reactive attenuators that rely on expansion chamber losses, and absorptive attenuators that rely on a combination of Hemholtz resonator and absorption, discussed by this author in greater detail in a 2004 paper on engine test cell noise emissions.

Reactive mufflers tend to be more effective at lower frequencies and have large pressure drop (aerodynamic flow resistance), while absorptive mufflers are more effective at higher frequencies with small pressure drop. Both types have maximum attenuation over a narrow frequency range, based on pipe inlet size, vessel volume and length: smaller for high frequency, larger for low frequency. Since the annoying tone from the vacuum pump discharge was a high frequency, an absorptive, straight perforated pipe muffler with acoustically absorptive fiber filler in the body was recommended, sized for maximum attenuation in 3000 Hz octave. The high frequency solution muffler is smaller, with a narrow diameter inlet and limited airflow, so individual mufflers were recommended for each pump discharge, in lieu of a single larger muffler in the discharge header, because the larger muffler would be less effective at high frequency.
Performance validation measurements have not been conducted, but the client reported the problem solved after installation of the high frequency muffler and vibration isolation solutions.

4. MRI MANUFACTURER’S ALLOWABLE FLOOR VIBRATION CRITERIA

Manufacturers of diagnostic imaging and other sensitive hospital and lab equipment often provide allowable vibration criteria as one element of required environmental, space, utility and service parameters for the installation location. Floor vibration can cause small magnet displacements that result in distortions or artifacts on the scan image. Magnetic resonance imaging systems (MRI) have large massive magnets that require high strength floors to accommodate the large concentrated floor load. Slab-on-grade floors are inherently better than column-supported or suspended slabs, because they have great bearing capacity and the contact with the sub-floor soil or compacted fill damps the floor slab, so that it exhibits little or no resonant amplification of vibration.

Large hospitals are complex facilities with many different functional occupancies (medical, administrative and other departments). In this author’s experience, rarely has it been possible to obtain slab-on-grade locations to install MRI or other diagnostic equipment, due in part to limited available space, but more importantly, because it would separate the equipment from the patient and medical staff spaces. As engineers, we therefore have consulted on several MRI’s on suspended slabs. The design parameters and vibration performance results of a specially designed high strength, high stiffness, vibration control slab for an MRI was discussed in a paper on floor design for an MRI at ICSV10, 20039. Recently, site evaluation floor vibration measurements were conducted to qualify a proposed basement slab-on-grade location for an animal research MRI10. The results of that measurement are shown here in contrast to the costly special design suspended slab, which was constructed for another MRI at the same institution. Because these two locations are within the same complex of buildings, they are subjected to very similar external ground borne and internal building ambient vibration conditions. The vibration amplitudes as a function of frequency are notable, because of the critically damped slab-on-grade, versus the resonant amplification that occurs to some degree in any suspended floor structure. Even damping from the large MRI magnet mass (at a concentrated location on a suspended floor slab) can not match that of full area contact with the ground or compacted fill.
5. CASE STUDY: MRI SCAN NOISE INTRUSION IN NEARBY OFFICES

A magnetic resonance imaging system (MRI) was installed in a clinic facility on a ground floor, column-supported concrete slab above crawl space. Demising partitions around the magnet room were designed and constructed to contain noise, yet physicians in nearby offices complained about annoying noise intrusion from the MRI. On-site observations with vibration and airborne noise measurements were conducted to determine disturbance sound level characteristics relative to permissible background noise criteria and possible paths of disturbance from magnet (source) to receivers\(^\text{11}\).

![Figure 6: MRI magnet and Receiver Room noise spectra before and after installation of vibration isolation pads.](image)

The MRI magnet as a source was apparent by the nature and timing of the intrusive noise audible in receiver offices. The path of transmission was less obvious. Sound levels were not measured in the magnet room of the subject facility, but similar equipment have been measured in other facilities to be approximately 100-110 dBA overall\(^\text{12}\). Intrusive noise in a representative office was approximately 56 dBA. Evaluation of the airborne sound path indicated that attenuation due to partition transmission losses, HVAC ductwork, and distance should result in a lower receiver sound level. Structure borne vibration, therefore was the most likely transmission...
path from the magnet to receivers. Vibration and noise spectra were measured in the magnet room. Spectra for vibration on the interior partition surface and airborne for noise were measured in the receiver room and compared to the source. Common prominent discrete or narrow bandwidth peaks showed conclusively that the airborne disturbance noise was caused by surface radiation of structure borne vibration that originated at the MRI magnet.

A noise control concept had to be developed to attenuate or isolate the structure borne vibration either (a) at the source, (b) along the path or (c) at the receiver. Potential concepts included (a) vibration isolation of the magnet, (b) structural isolation break in the concrete floor slab and (c) resilient remounting of partition and ceiling surfaces in receiver rooms. By observation and judgment, it appeared that the (physically) closer the solution to the source, the less extensive the modifications would have to be. Because it was an existing business with an on-going clinical practice, down time and possible demolition complications to physician offices were deemed not feasible. Cutting the MRI magnet room floor to achieve a structural isolation break was not favored by the clinic because of the messy invasiveness and the necessity for adding new columns to support the magnet slab. The MRI manufacturer’s technical representatives were not in favor of disturbing the magnet installation to improve vibration isolation. No isolation was incorporated in the base, even though their own installation details provided for vibration isolation options. All of the most obvious and basic vibration mitigation solutions had potential drawbacks that caused resistance by the client, but the favored solution was to insert vibration isolation pads between magnet feet and the floor slab. This solution would require no demolition or reconstruction in any space, but it would require a rigging contractor with the ability to lift a large mass of 5455 kg (12,000 lbs) within the magnet room enclosure. Also, liquid helium, in which the magnet is immersed to keep it cool during operation, would have to be dumped before lifting the magnet and replaced afterward, adding difficulty and cost to the retrofit. Following budget and feasibility considerations, the Client selected magnet isolation.

After 25 mm (1 in.) thick vibration isolation pads were installed beneath the magnet feet, the noise intrusion problem improved, but did not go away. The consultant and client, however, found a possible vibration-flanking path at the magnet mounting points that permitted the magnet vibration to bypass the newly installed isolators. An isolator with greater thickness 38 mm (1.5 in.) was recommended, which would result in breaking the flanking path. The recommended isolator would also have greater static deflection, which would result in better performance with respect to frequency range and amount of attenuation.

Measurement results comparing before and after conditions show a 15 dBA noise reduction. The client reports satisfaction of physician complaints.
6. CONCLUSIONS
Medical health care and research facilities have many noise and vibration sources. A variety of sensitive receivers that include humans and inanimate instruments and equipment are affected by excess noise. The case studies above show that vibration and noise are integrally tied. Both should be considered at the source, along the path and at the receiver to assure complete consideration of relevant conditions. Narrowly focused analyses of one or the other may yield incomplete or partial solutions that fail to satisfy all criteria.

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