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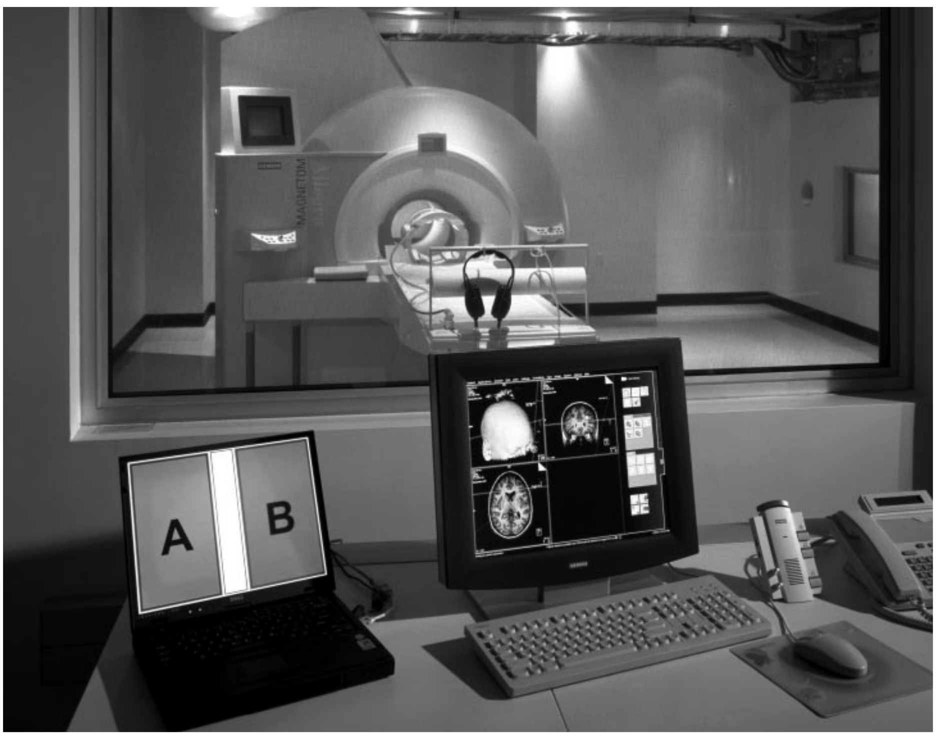
ABSTRACT

This is a case study about noise and vibration control problems, and the design constraints and solutions for a proposed installation of a magnetic resonance imaging system (MRI) in an existing medical research facility. Manufacturer's data indicated that airborne sound level emissions over a broad frequency span could exceed permissible noise criteria for nearby occupied rooms. The building structure also required reinforcement to accommodate the MRI magnet's concentrated load, but invasive disturbance to a transgenic research mouse vivarium on the floor below was prohibited. The structure borne vibration paths needed attenuation or isolation. Design parameters included structural strength, stiffness and the specific platform resonant frequency (non-coincident with known vibration sources or building structure). In addition, acoustical containment was required for anticipated noises from the magnet room, to prevent excessive or annoying and distracting noise in the MRI control room or other adjacent (but unrelated) research, animal holding and office spaces. Structural "de-tuning" and architectural "decoupling" concepts were employed. A resonant frequency criterion was recommended for the new structural floor design. A combination of vibration spectrum analysis, dynamic analyses of alternate structural concepts and existing physical conflict constraints led to the design of an independent platform floor above the existing building floor. Post construction floor vibration measurements were compared to earlier measurement data to show quantitative change in performance. The modifications satisfied acoustical criteria and occupants' subjective evaluations.

INTRODUCTION

A Human Neuroimaging Laboratory proposed a magnetic resonance imaging (MRI) suite that would incorporate two research MRI's in individual rooms separated by their respective control rooms. Floor vibrations were to be severely limited in the new installation, in order to avoid degradation of the images produced by the new machines. The MRI magnets exert large concentrated loads on the floor structures, which were originally designed for ordinary occupancy. Structural reinforcement was required to accommodate these increased loads. The large magnet assemblies generate moderate noise during startup and scan sequences, which could be transmitted to adjacent spaces by airborne and structure borne paths. Therefore, prerequisite vibration and noise control were important for the architectural and building system designs. MRI equipment modification, to reduce source noise and vibration generation, was not included in the scope of work. The proposed suite was above a transgenic research mouse vivarium, and below research laboratories, and was situated between unrelated office spaces (see Figure 1)



View of MRI Room From Control Room

The vivarium is a very sterile environment. Initial feasibility studies determined that the necessary structural reinforcing could not be done below the floor structure without contaminating the vivarium. Therefore an alternate design concept was developed involving a separate structural platform above the existing floor. The elevated floor structure was to span three structural bays of the building and be independent of all building elements, except for beam connections to the building columns. The floor vibration control design concepts are presented below.

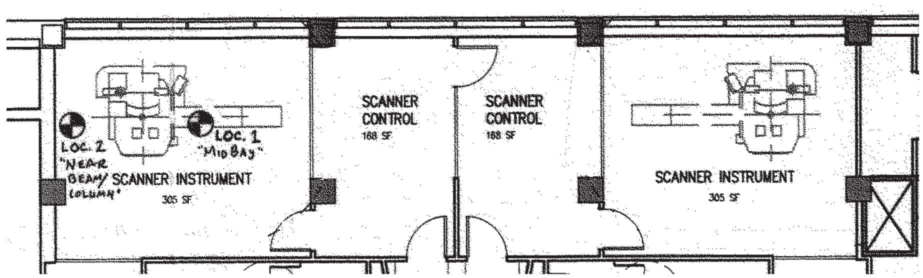


Figure 1. Plan view of proposed MRI Suite showing pre-design vibration measurement locations 1 & 2

Decoupled mass design concepts were employed for partition, floor and ceiling assemblies, because both airborne and structure borne noise paths were anticipated. Double leaf assemblies have been shown to have greater transmission losses than monolithic panels, and decoupled assemblies have greater transmission losses than either monolithic panels or double leaf assemblies.[1] Other design considerations included various means of preventing flanking noise transmission paths via doors, air conditioning ducts and other penetrations for pipes and conduits.

EXISTING CONDITIONS

Vibration measurements were conducted in three mutually perpendicular axes (x, y, z) on the building floor, prior to initiating design, for the purpose of determining the existing building floor ambient vibration spectra and resonant response to transient excitations impact. This data was to be compared with the MRI manufacturer's allowable vibration criteria.

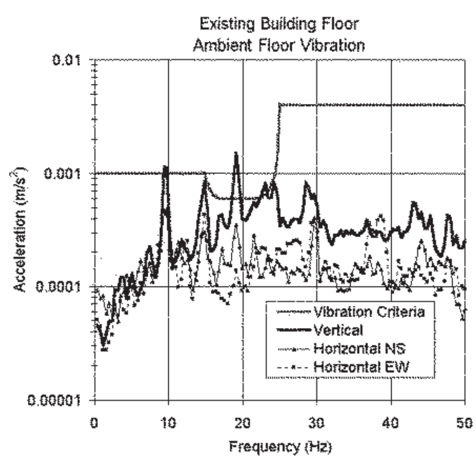


Figure 2. Ambient vibration vs. criteria

This allowed the determination of the design parameters for the proposed platform floor structure. In Figure 2 it is shown that the horizontal vibration levels (X and Y axes) complied with Criteria. In the vertical direction, narrow band peak levels (L_{eq} and L_{max}) were apparent at 9.5, 15, 17, 19, 29 and 30 Hz, indicating continuous disturbance. An L_{max} peak was also evident at 23–24 Hz, but not in the L_{eq}, indicating transient disturbance. In particular the 9.5, 19 and 23–24 Hz frequency peaks exceeded the permissible criteria.

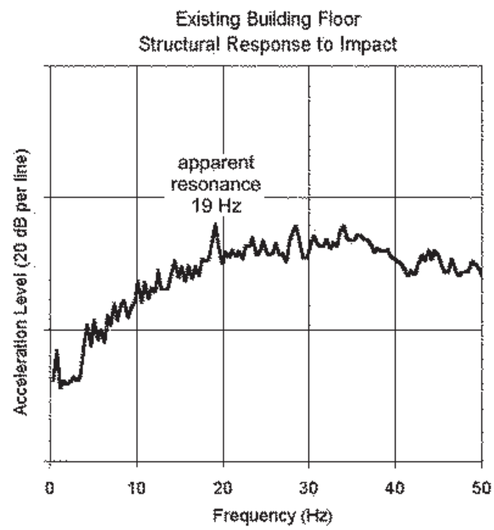


Figure 3. Apparent resonance

In Figure 3 the structural response to impact excitation gives an apparent resonance at 19 Hz, with a harmonic at 38 Hz, and appeared coincident with a continuous source.

Concomitant vibration measurements, in mechanical and electrical equipment rooms, identified an air handler (fan), pump and pipe, small refrigeration chiller, electrical transformer and switchgear as sources of the vibration (note: North American standard electrical frequency of 60 Hz results in a 30 Hz sub-harmonic).

PRIOR CONDITIONS AND SOURCE NOISE

Airborne sound measurements were conducted in the MRI and adjacent office/conference spaces before design. Measurements were conducted before and during the design process in the existing vivarium (below) and laboratory space (above),[2] respectively, to determine minimum, "normal" and transient maximum levels. The equivalent level (L_{eq}) was used to represent normal or average condition. ASHRAE background design guidelines were used for the proposed MRI control rooms and adjacent office and conference spaces.[3]

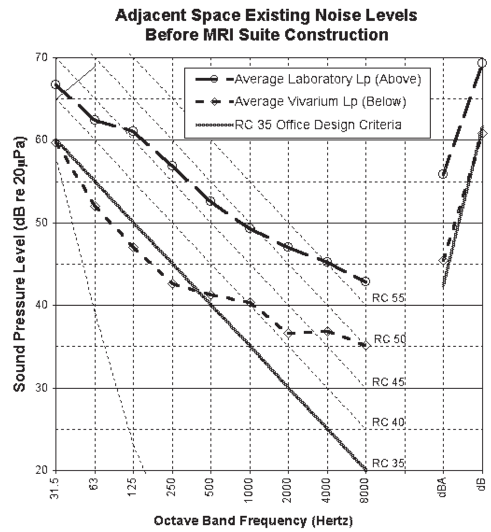


Figure 4. Prior ambient sound levels and RCs

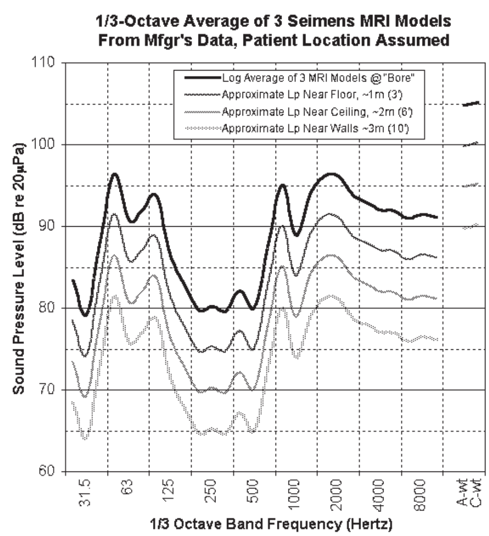


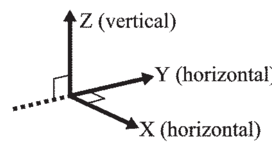
Figure 5. Prior MRI source levels

In Figure 4 the average sound level in the vivarium animal holding and procedure rooms (below the MRI) was 45 dB(A). The level exceeded the RC 45 line, near rodent peak hearing sensitivity, 2–4 KHz. The average sound levels in the research laboratories (above MRI) was about 55 dB(A), and near RC 50 in the human speech/peak hearing sensitivity frequency range, 250–2000 Hz (Figure 4).

In Figure 5 are shown the sound pressure level data for three MRI models,[4] giving an overall average of approximately 105 dBA at the source.

VIBRATION CRITERIA

The MRI equipment manufacturer provided proprietary allowable vibration criteria[5] to the system purchaser for the installation design. A modified generic version is presented here. The maximum (peak hold) narrow band value was not to exceed acceleration (rms) amplitude in the x, y or z axis, as follows:



0 – 25 Hz: (varies) ~.0006 – .004 m/s^2
25 – 50 Hz: ~.004 m/s^2

Greater vibration could be tolerated if special vibration isolation pads were integrated in the MRI magnet installation.

NOISE CRITERIA

Noise criteria in adjacent spaces varied with the functional requirements of the different rooms. Transmission loss noise reduction requirements for wall, floor and ceiling would be equivalent to the differences between the source noise level and the receiver room ambient levels, plus a small allowable "audibility" or exceedence over ambient. Although speech interference or articulation index analyses were possible, for this project it made sense to base noise containment decisions on avoidance of distraction and annoyance. Therefore, it was decided that the magnet-scan noise be no louder in adjacent spaces than ambient sound level, or just a few dB above ambient levels in the receiver rooms. Measurements of continuous ambient noise levels were used to establish permissible noise for the existing vivarium and laboratory spaces. ASHRAE continuous noise criteria for office and conference spaces were used, as follows:

$$TL_{NR} = Lp_{source} – Lp_{receiver} – C_{allowable} \quad (1)$$

where:

TL_{NR} = Transmission Loss through wall, floor or ceiling
Lp_{source} = Siemens MRI noise emission (distance adjusted)
$L_{preceiver}$ – Receiver room ambient sound level
$C_{allowable}$ = audible exceedence above receiver room ambient

The research mice in the vivarium below the MRI are expensive and the institution conserves costs by reproducing the mice. Excessive noise and vibration can stress mice, resulting in decreased feeding and reproduction rates. Therefore noise should neither be louder nor more tonal than the background noise, especially at frequencies near 4 KHz, the peak sensitivity of rodents. Therefore, the design goal was to prevent audible MRI noise intrusion. In Figure 6(a) this gives TLNR ~ 100 – 45 – 0 = 55 dB(A).

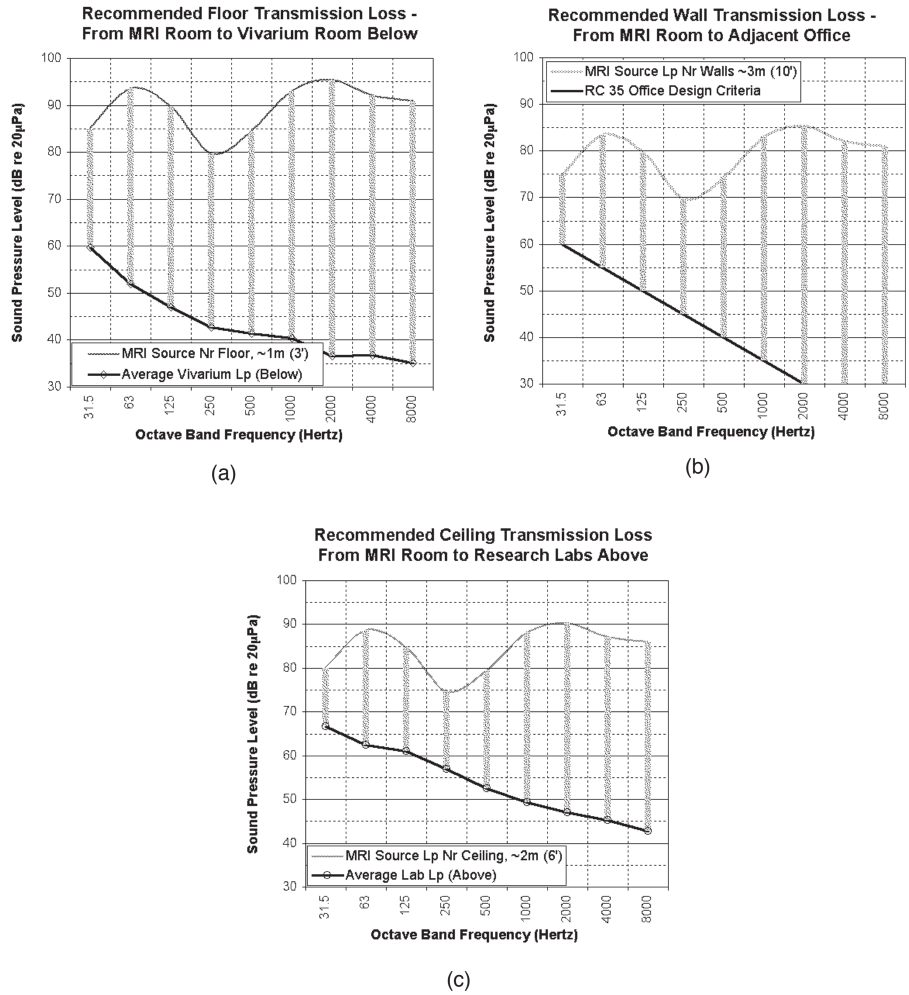


Figure 6. Difference between MRI sound level and adjacent ambient level and criteria.

For adjacent office and conference spaces (Figure 6(b), intrusive noise criteria were established to prevent speech interference, distraction and annoyance. Audible MRI noise would be permitted, but not more than 3 dB above the anticipated ambient sound level (re: ASHRAE), therefore TL_{NR} ~ 90 – 42 – 3 = 45 dB(A).

The wet and dry laboratories above the MRI suite are less susceptible to interruption of speech communication or distraction (Figure 6(c)), and can permit short duration transient intrusive noise. MRI noise up to 6 dB above the ambient sound level can be tolerated, therefore TL_{NR} ~ 95 – 56 – 6 = 33 dB(A).

OBJECTIVES AND STRATEGY

Additional objectives were to develop vibration and noise control methods that would be compatibly integrated into the other structural and architectural requirements. A platform deck, on the floor slab, acts as a decoupled mass noise barrier, although some structure borne flanking was anticipated via the structural connections at the building columns. The platform could also accommodate decoupled partition assemblies. Resilient suspension of the MRI room ceiling would supplement the sound and vibration isolation to the spaces above. By utilizing decoupled mass barrier concepts for MRI acoustical isolation from adjacent spaces, a "room-within-a-room" concept, structure borne and airborne noise transmission paths can be attenuated.

A "de-tuning" strategy was also proposed to target a moderately high-frequency structural resonance to be non-coincident with identified existing disturbance frequencies. In other words, make the platform structural resonance occur at a frequency where ambient building vibration is moderate. A platform resonant frequency of 25–26 Hz was initially proposed, but the structural engineering analysis indicated excessively large moment reactions at building column connections. Therefore, a 12–13 Hz resonance was recommended, because it was at least 2 Hz higher or lower than existing disturbance frequencies, and structurally feasible as well. Therefore the vibration control recommendations included a design MRI platform floor structure at a 12–13 Hz resonant frequency, to be non-coincident with building floor resonance and building systems' disturbing frequencies. The suite's partitions were to bear on the existing building floor, immediately adjacent to the platform floor, but were not to be not connected to it, in order to limit building vibration transmission paths to the platform floor. Internal suite partition framing could bear on the platform slab, but could not be connected to the building. The central control room bay could be less stiff than the two magnet bays, which would result in less magnet-generated vibration being transmitted bay-to-bay due to dissimilar structural resonances. Deep structural channel

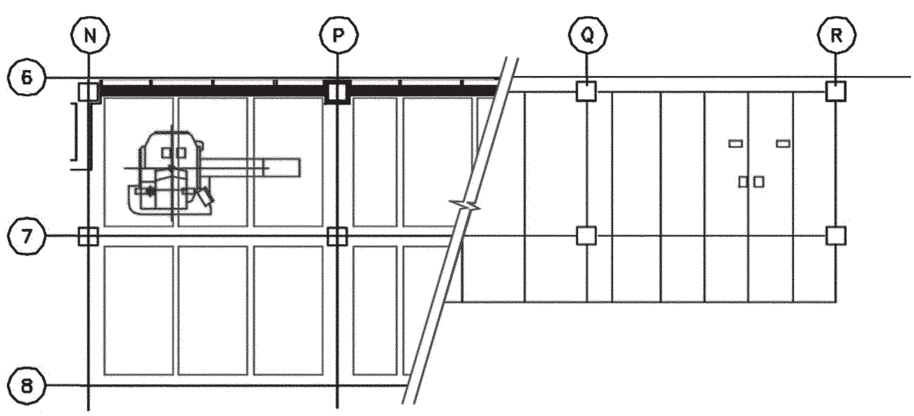


Figure 7. Composite plan: existing floor (left) and proposed platform (right)

Figure 8. Platform frame above floor

Figure 9. Partition framing and shielding

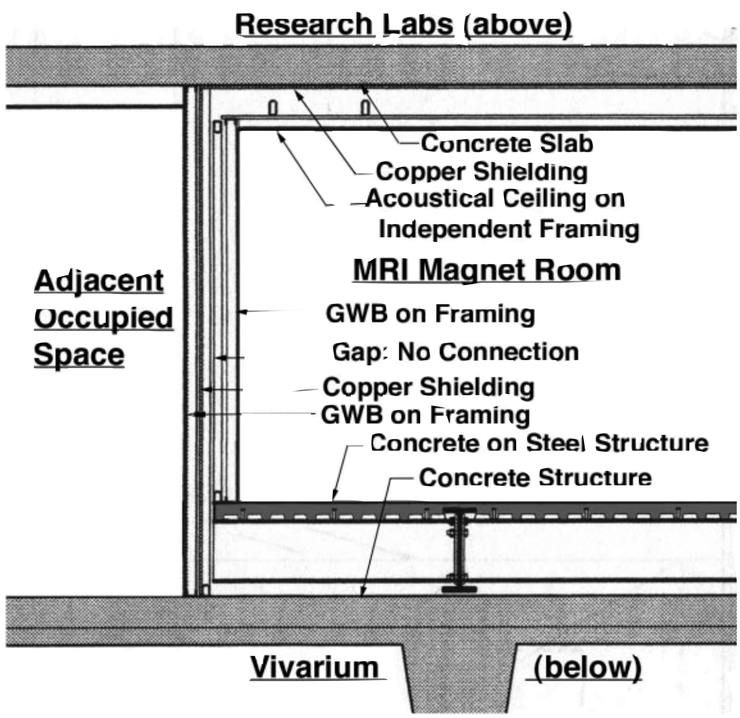


Figure 10. Section view: decoupled barriers

members were to be provided on the perimeter of the platform slabs, to stiffen edges against distortion due to torsion, bending or other vibration-induced reactions.

Building equipment, pipes, conduits and duct supports and hangers were identified that required vibration isolators or isolator adjustment to relieve existing flanking conditions. The isolators were be effective down to frequencies below the 9 Hz (lowest frequency) disturbance.

Acoustic and noise issues, although not central to the floor vibration control design, included containment of the magnet generated noise and assurance of air conditioning equipment noise compliance with ASHRAE continuous noise criteria.[6] Sound transmission class (STC) test results were reviewed for the floor–ceiling assemblies above and below the MRI rooms, and for the partitions enclosing the suite. The partitions were recommended to have several layers of gypsum board (mass), in combination with copper sheet electromagnetic shielding, to achieve high sound transmission losses. Acoustic seals were recommended on doors. Supply and return air ducts were designed to attenuate fan and air terminal noise as well as maintaining the partition noise reduction. Ceilings were recommended with moderately high transmission loss products and vibration isolation hangers.

By comparing the STC's with recommended noise reductions, the remaining additional sound transmission loss requirements were determined.[7] The floor-ceiling assembly above the MRI room was adequate to achieve the required approximate 33 dB(A) of noise reduction. Independent and resilient support of the ceiling and shielding assured isolation of the structure borne path as required. For offices horizontally adjacent, a double stud drywall assembly with at least three layers of gypsum board was adequate to achieve the required approximate 45 dB(A) of noise reduction. The inner stud framing was placed on the platform structure, and the outer studs were placed on the structural floor, resulting in decoupled inner and outer partition elements.

For the vivarium below, the structural floor and ceiling assembly below the MRI was inadequate to achieve the required 55 dB(A) of airborne noise reduction. The addition of the platform floor above the structural floor provided substantial additional decoupled mass with a large air space.

Design integrity required identification of potential flanking paths, such as duct, pipe and conduit penetrations. Flexible connections were recommended between decoupled elements of assemblies. Duct attenuation and lagging (enclosure of ducts) were recommended near wall and structure penetrations. A proposed duct routing within the room was recommended to be relocated outside the room for noise control.

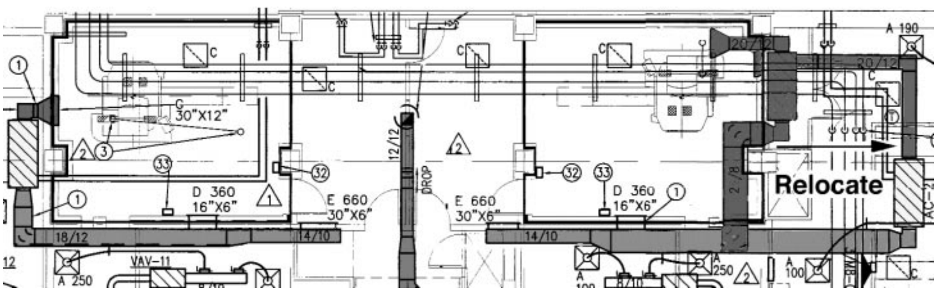


Figure 11. Mechanical plan: ducts modified to achieve noise containment, including relocation of penetrating duct out of MRI room and duct lagging near penetrations

DESIGN IMPLEMENTATION

The architect and structural engineer agreed to implement all major vibration and noise control recommendations. After conceptually designing the beam and joist frame with concrete deck for the platform structure, the structural engineer conducted a Murray vibration perception analysis[8] and a finite element analysis (FEA) to confirm stiffness, stability and desired resonant frequency. Design refinements were made, including depth increases of perimeter members to stiffen edges, for the purpose of resisting shape distortions that might occur in response to transient vibration excitation or impact. Building systems (mechanical, electrical and plumbing) noise containment and control recommendations were adopted, except where existing physical conflicts prevented implementation.

Decoupled double stud wall inner and outer parts were erected separately on the platform and structural floors, respectively. Wall penetrations and interfaces with

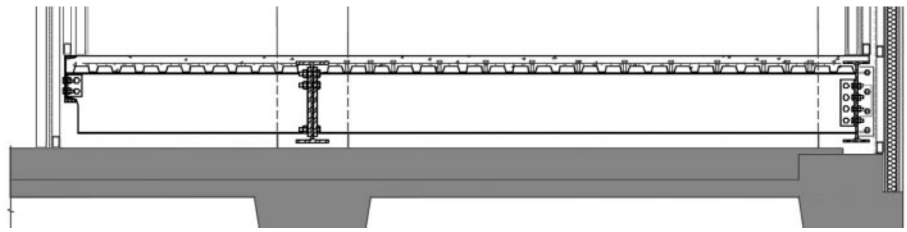


Figure 12. Section: Decoupled partitions at platform structure

structure were sealed airtight. Air conditioning supply and return duct penetrations were permitted only for diffusers and registers. Ceilings were planned with vibration isolation hangers, and doors and windows were specified to achieve necessary sound isolation and electromagnetic shielding. Door and window elements between MRI and Control Rooms were specified to achieve necessary sound isolation and electromagnetic shielding.

POST-CONSTRUCTION PERFORMANCE VALIDATION

Vibration performance validation measurements[9] were conducted on the completed platform structure before the partition framing was erected or the magnets were installed. Weights were stacked on the bare platform floor in the vicinity of the magnet mounting points to simulate the dead loading in Figures 13 and 14. Vertical and horizontal vibration, shown below, complies with criteria, including the structural resonance at 12–13 Hz.

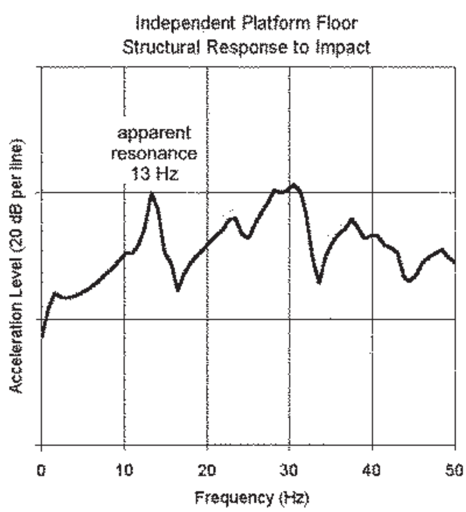


Figure 13 Apparent resonance

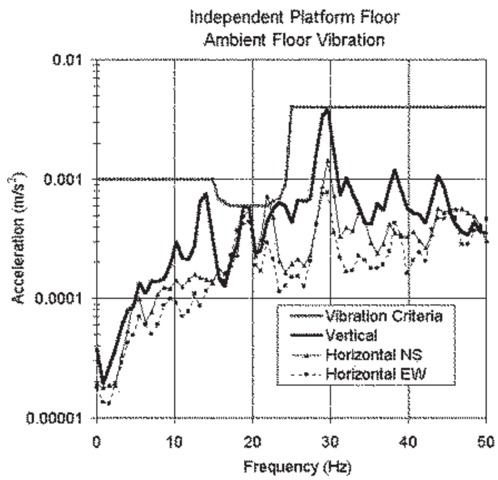


Figure 14. Ambient vibration vs. criteria

Ambient noise and sound transmission performance validation measurements were conducted after the facility was occupied.[10] Measurement locations included an MRI Room, a Control Room and the adjacent "Hyperscan" office (see Figure 16). The spaces were in "normal use." Although the vivarium could not be tested, no noise intrusion complaints were received from the vivarium or laboratory managers.

MRI scan sequence noise emission L_{eq}'s are shown in Figures 15 and 16, indicating levels and tonality.

Sound transmission measurements were made in general accordance with ASTM E 336, Measurement of Airborne Sound Insulation in Buildings, except that source room

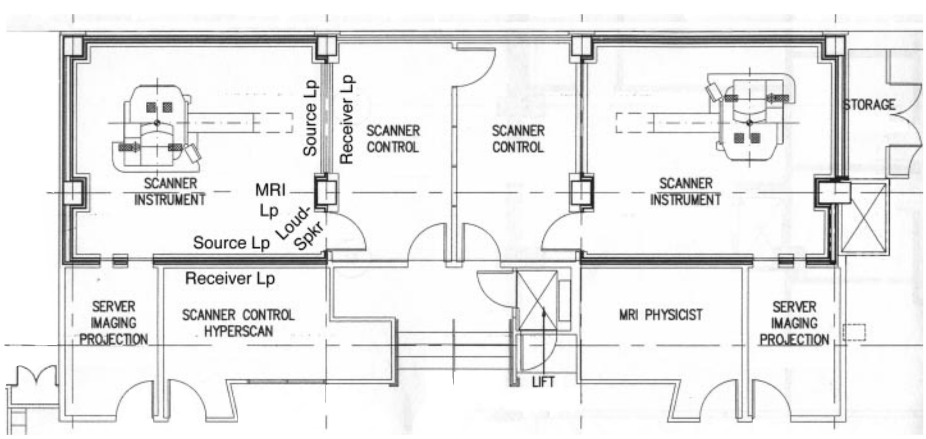


Figure 15. Plan view of proposed MRI suites howing post-occupancy sound measurement locations

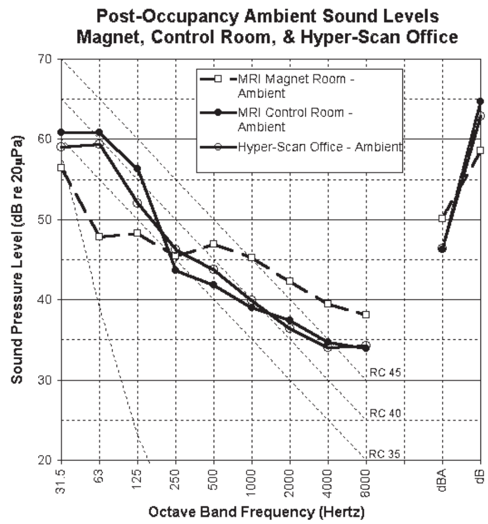


Figure 16. MRI Suite ambient noise levels

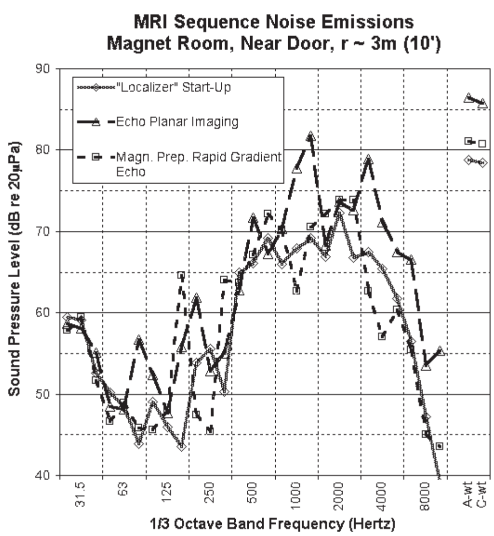


Figure 17. MRI scan sequence noise spectra

measurements were made less than 1 m from walls, because metallic items are not permitted near the MRI magnet due to the magnetic fields. Receiver measurements were 1 m from partitions.

On-site observations and measurement results (above) showed that the MRI to Control Room sound containment was limited by the window and door, but achieved NIC 34. The MRI to "Hyperscan" Office decoupled double stud partition achieved

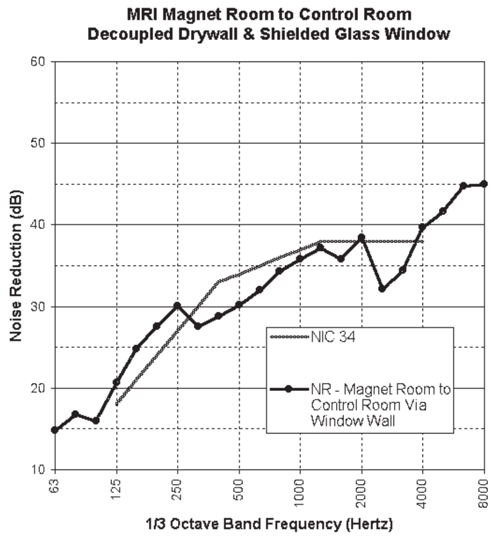


Figure 18. Control room noise reduction

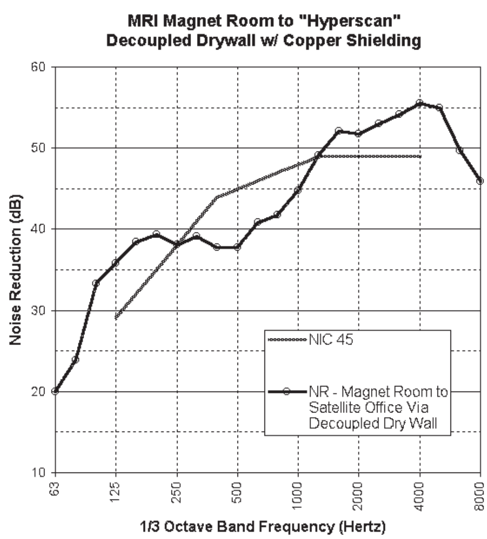


Figure 19. HyperScan office noise reduction

NIC > 45. Transmitted test sound levels in the Hyperscan receiver room were very similar to the ambient, indicating at or below ambient results.

CONCLUSIONS

This project utilized strategies of de-tuning structural resonances and de-coupling of partitions and other elements that could transmit vibration to the magnet platform structure. Existing building floor resonance frequency and disturbing vibration sources were identified prior to design.

The magnet floor structure was designed to have a resonance frequency non-coincident with other building resonances or disturbing frequencies, using dynamic analysis to confirm design parameters prior to construction. In response to the challenging requirements of the installation, the structural engineer developed an economical combination of stainless (non-magnetic) and carbon steel framing to support the magnets. Existing vibration source vibration isolation was improved. The final result achieved all objectives (without disturbing the vivarium below), demonstrating the simplicity, elegance and effectiveness of de-tuning and de-coupling to achieve vibration control.

Users have reported excellent operational results, with no artifacts or other image abnormalities. Magnet noise transmission is not annoying in waiting, control room or office spaces near the magnet rooms. The vibration and noise control strategies and implementation are complete successes.

ACKNOWLEDGEMENTS

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