Vibration Isolation of a Medical Facility

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An MRI (magnetic resonance imaging) facility was constructed only 50 ft from a busy railroad line. This case history shows how careful design, analysis, testing and construction can provide a completly successful solution to a very severe problem.

The University of Pittsburgh Medical Center (UPMC) Sports Performance Center in Pittsburgh, PA, was completed in September 2000. The center combines training facilities for the Super Bowl XL champion Pittsburgh Steelers and the University of Pittsburgh football teams together with the world class UPMC Center for Sports Medicine. The Sports Medicine Center offers comprehensive and advanced sports medicine care by world-renowned physicians, orthopedic surgeons, athletic trainers, and physical therapists in state-of-the-art facilities. The center treats patients from teams like the Steelers and Penguins (professional hockey), collegiate athletes from the University of Pittsburgh and Penn State University, performers from the Pittsburgh Ballet, scholastic and weekend athletes along with nonathletes.[1,2] The capabilities of the center are succinctly stated by one of its departmental directors: "This is unique in that we have everything under one roof – physicians, physical therapists, sports nutrition, sports psychology – it's all here in one building."[3]

The UPMC Sports Performance Center is a part of an urban revitalization project located on land that until the 1980s housed a Jones & Laughlin Corporation (later LTV) steel plant. The narrow half-mile strip of land is bordered on one side by the Monongahela River and on the other side by a CSX rail line. The rail line is one of the busiest in the Eastern United States. More than 60 trains per day pass on an unpredictable schedule.[2] The center's close proximity to the CSX rail line can be seen in Figure 1.

As part of medical diagnostic capabilities of the Sports Medicine Center, it has an MRI (magnetic resonance imaging) unit. Modern MRIs are extremely sensitive to foundation vibrations. Vibration requirements vary with MRI vendors, but the leaders have similar site requirements for 1.5T (Tesla – a unit of magnetic force) and 3.0T units. Vendors require vibration levels below 100-450 µg in the 0.5-100 Hz frequency ranges, with an emphasis on levels below 100 µg in the 0.5-50 Hz range. Foundation vibrations in excess of these values are likely to adversely affect image quality with ghosting and artifacts, especially for more stringent scans.

The UPMC's original 0.7T MRI was located approximately 50 ft from the rail line in the corner of the building (Figure 1). This MRI was installed on a concrete slab at grade. In the absence of train traffic, ambient environmental vibrations of normal activities in and around the center satisfied the MRI manufacturer's vibration specifications. However, when a train passed scanning had to be terminated due to excessive vibrations. The unpredictable train traffic caused delays and scans to be repeated.

In 2005, the Sports Medicine Center wanted to replace and upgrade its MRI with a new 1.5T unit, which has more stringent vibration requirements. Furthermore, UPMC wanted to eliminate all MRI operational disruptions caused by train traffic. Preliminary site tests demonstrated the expected result: high vibration levels exist, and typical slab construction, even with a heavy inertial mass, would not satisfy the more stringent vendor specifications. UPMC's architect was told that a floating floor concept should work. However, the combination

Figure 1. USX rail line adjacent to UPMC Sports Medicine Center building.

of the severe railroad-induced vibration environment and the demanding vendor requirements created a situation where a successful outcome was not assured. To increase the probability of success, a very conservative multistep design, testing, and analysis process was implemented. The staged approach had both technological design and project management benefits:

1. The isolation system development used an iterative process to optimize the design with regard to reducing vibration and cost. The knowledge gained at each step helped eliminate inherent design uncertainties and allow more accurate modeling and performance predictions. The constant design refinements increased the probability of ultimate success.
2. A project *go* or *no-go* decision was based on the iterative process, and UPMC could terminate the project if a significant probability of failure was identified. Otherwise if a high likelihood of success continued at each step, the project would move forward until the MRI was fully operational.

A preliminary review of possible design alternatives in relation to the site constraints was performed. The review resulted in recommending an array of helical springs supporting a carefully designed concrete slab. This choice was made over the more complex approach using active pneumatic springs, because it was much less costly and maintenance free. To design and construct the isolation concept, a team consisting of vibration engineers, an isolation component vendor, an architectural firm, structural engineering firm, and a construction company was assembled. The vibration engineers were charged with the responsibility of designing the system and helping with its implementation. The objectives were to:

1. Provide adequate isolation so that the site would meet the vibration requirements of the MRI vendor's 1.5T unit.
2. Design an electromagnetically shielded room so that the floor would not have relative motion between the MRI and the shielding room's environment.
3. Allow MRI scans to be successfully performed without ghosting or artifacts in the images while trains passed by.

The design process and performance evaluation at each of the multistaged steps are discussed in the following sections.

Vibration Characterization

The first task was to characterize the ground vibration at the MRI site due to the train traffic. High-sensitivity seismic accelerometers (PCB393, 10 g/v) were deployed surrounding the site. Vibration data were acquired for approximately 50 trains

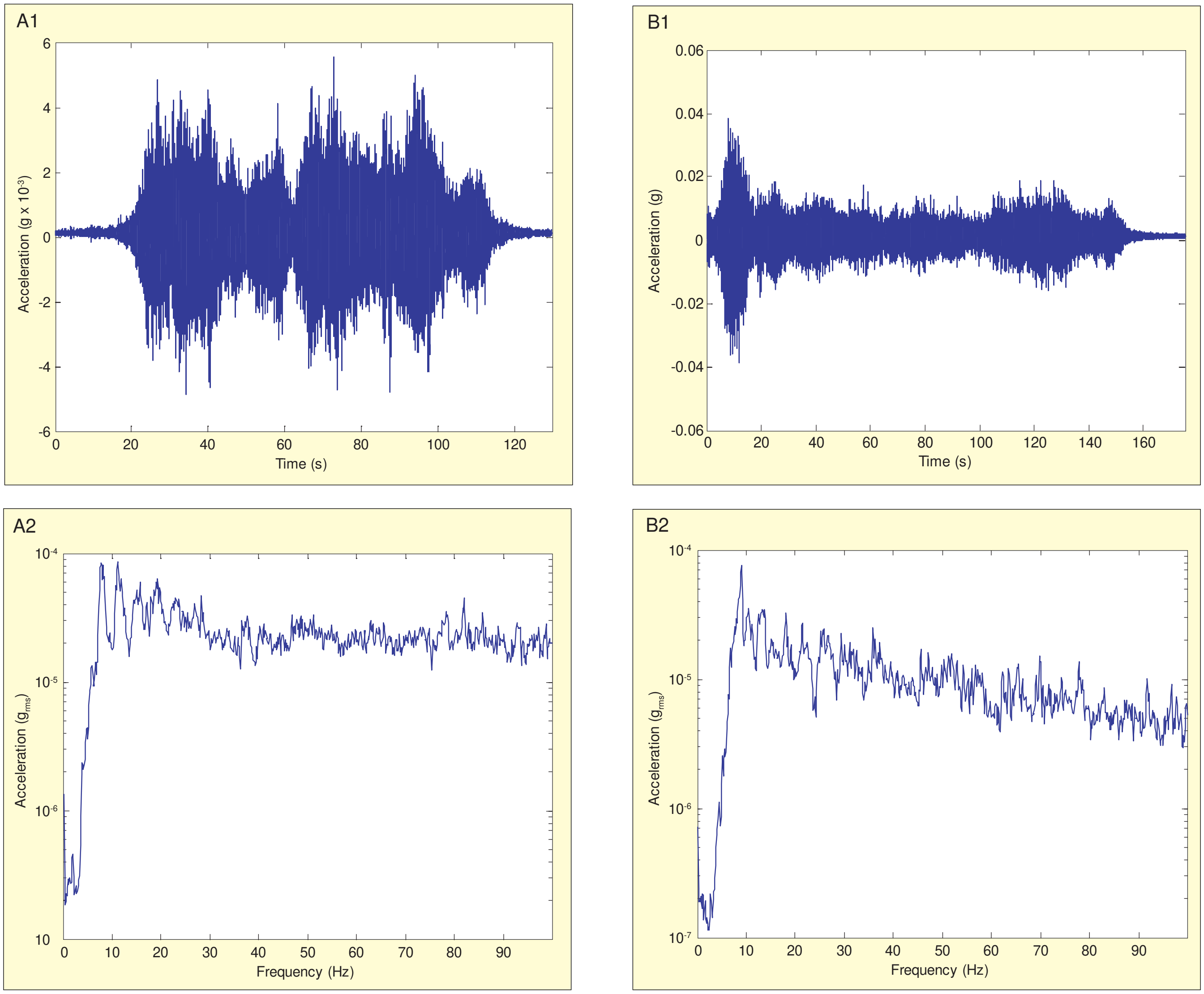

Figure 2. Typical ground vibration time traces and averaged spectra for two train pass-by. Train A – Mixed freight with tankers, flat bed and boxcars; Train B – Loaded car carrier.

at different times of the day over a two-month period to fully characterize the environment sufficiently to set the isolation design metrics. The train cargo varied from empty rolling stock to fully loaded coal and tanker cars. The train speeds of about 27 MPH as measured with a radar gun resulted in a typical train passage lasting approximately 1 to 3 minutes. The ground vibration time histories for two typical trains are shown in Figure 2. While the vibration signature of each train has some similarities each is also quite different, depending on the number of locomotives (normally two to four) and rolling stock. The highest peak vibration levels often occurred when the locomotives passed, as shown in the first 20 sec in Figure 2A1. Acceleration time histories showed that freight train passage creates ground vibration with very nonstationary characteristics. The vibration tends to have semiconstant levels punctuated with intermittent high-level discrete transient events. Flat spots on the car's steel wheels often caused these high-amplitude transient events. Since hard braking is the root cause of the wheel flats, individual cars may have multiple wheels affected by the phenomena. For a given measurement location, the impacts from each affected wheel would increase and then recede as the car passed. Trains are often interspersed with many cars exhibiting this behavior.

The respective spectra estimated for these train vibration signals are shown in Figures 2A2 and 2B2. The spectra are computed over the critical 0.5-100 Hz frequency range for the MRI. The spectra were estimated with a Hanning widow and a frequency resolution of 0.125 Hz using overlap processing to maximize the number of averages available from the time arrays. Inspection showed low vibration levels below 5 Hz and relatively higher constant levels across the balance of the critical frequency range to 100 Hz. Some harmonic content was often apparent due to periodicity related to the interaction of rolling stock wheels and rails.

The discrete transient events in the train pass-by produce temporally localized high-amplitude vibration along with steadier vibration induced by the rolling stock. These transient events and pseudo-steady-state vibrations will adversely affect the MRI performance and they must be carefully evaluated to ensure effective isolation will be achieved to meet MRI vendor requirements for the site. The ensemble averaging across the entire time history is an aggregate spectrum and does not provide the necessary characterization of the normal vibrations and the transient events. To provide the necessary spectral detail of the transients, a short-time Fourier transform (STFT) was applied.[4] The STFT for the train vibration in Figure 2A1 is shown in Figure 3. The STFT produces a three-dimensional analysis of the frequency content with respect to time. The analysis shows relatively constant high-amplitude response below 20 Hz for the entire time record. The higher frequency content out to 60 Hz at the beginning of the time record is caused by the locomotive. Occasionally high-amplitude values up to 100 Hz are readily apparent at distinct times. This content results from the transient events caused by the rolling stock wheel interaction. The application of the STFT proved to be well suited to the nonstationary nature of the train ground vi-

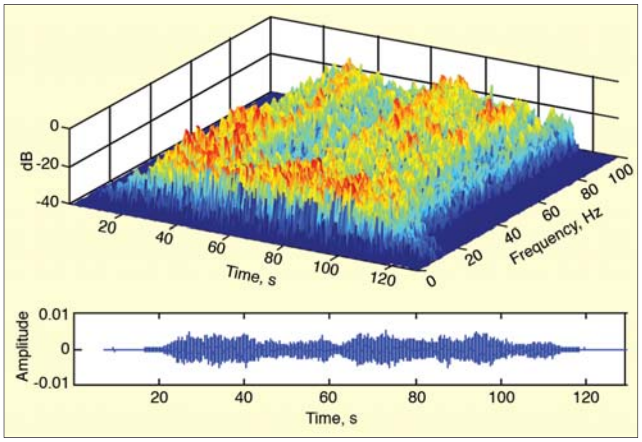

Figure 3. Short-time Fourier transform of ground vibration for train pass-by in Figure 2A1.

bration. The analysis characterized the potentially troublesome transient events and provided valuable input into the isolation system design and evaluation.

Analysis of the time histories, averaged spectra, and STFT quantified the environmental ground vibration necessary to establish engineering metrics to guide the isolation system design. But from the viewpoint of MRI site qualification, different vibration metrics are used. Typical MRI site compliance criterion uses the maximum value observed in each spectral line over a specified observation time. A Hanning window is usually used without overlap processing. The MRI manufacturer for each respective model establishes the acceptable vibration levels. This criterion is appropriate for stationary phenomena. However, for a mixed signal with a combination of continuous and strong transient events, such as a train pass-by, the risk of obtaining an inaccurate assessment exists.[5] The two primary reasons are:

1. The transient's amplitude can be affected by applying the Hanning widow if it is not captured in the middle of the record.
2. In a worst-case situation, there is a possibility that a short-duration strong transient may not be captured at all. This scenario is encountered when the transient event temporally occurs between the vibration segments analyzed.

The STFT analysis in Figure 3 clearly shows the high spectral amplitudes produced by the transient events. The maximum spectral line qualification criterion is very sensitive to these high-amplitude, short-duration events; therefore, their inclusion in the processed data is crucial. To ensure accurate qualification assessment, the train pass-by vibration was captured in its entirety and analyzed using an approach that processed all events. The analysis method used the maximum spectral amplitude criterion, and the strategy employed in the STFT processing is described below.

The Fourier Transform for a signal $x(t)$ is:

$$X(f) = \int_{-\infty}^{\infty} x(t) e^{-i2\pi ft} dt \quad (1)$$

A window function $w(t,T)$ is used to relate the continuous signal $x(t)$ to the finite sample:

$$x(t,T) = x(t)w(t,T) \quad (2)$$

The window function is only defined between 0 and T, being zero elsewhere. The Fourier Transform of the windowed sample is:

$$X(f,T) = \int_{-\infty}^{\infty} x(t)w(t,T) e^{-i2\pi ft} dt \quad (3)$$

Next, let the window function $w(t,T)$ include a time-shift variable τ and its Fourier transform becomes:

$$X(f,T,\tau) = \int_{-\infty}^{\infty} x(t)w(t,T,\tau) e^{-i2\pi ft} dt \quad (4)$$

By monotonically increasing the time-shift variable τ the window 'slides' through the entire data set $x(t)$. The respective Fourier transform is then computed at each incremental τ

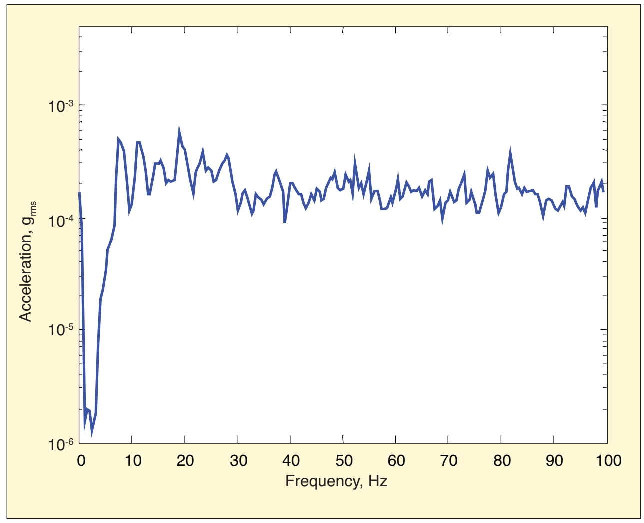

Figure. 4. Maximum spectral amplitude for train pass-by in Figure 2A1 using 90% overlap sliding-window approach.

value. This "sliding window" process is the basis of the STFT used to create the analyses in Figure 3. For vibration compliance evaluation, Equation 4 is used to create the spectrum in terms of g_{rms} for each incremental value of the shift variable τ. The shift increment is selected so that an overlap of 90% of the preceding sample is obtained. The maximum value observed in each spectral bin from all the samples is then retained as the window slides though the entire vibration time history. This analysis process ensures that the effects of all discrete transients are captured and used in the assessment criteria. A typical maximum spectral response computed by this method for the train ground vibration in Figure 2A1 is shown in Figure 4. This analysis will be used for compliance evaluations in all subsequent isolation system development steps.

Vibration Isolation System Design

The fundamental vibration isolation approach entails placing the MRI on a large inertial mass supported by a suspension with low rigid body resonant frequencies. Similar inertial mass designs have been used for isolating a variety of vibration-sensitive equipment. Successful applications have been reported in advanced metrology,[6] photon research laboratories,[7] and medical equipment.[8] All these designs used pneumatic springs, which produced rigid body resonant frequencies in the 1-3 Hz range. These applications provided sufficient isolation in less harsh ground vibration environments with a more stationary type excitation than the type observed near the railroad.

The proposed UPMC Sports Performance Center isolation system design solution entails placing the entire MRI room on an inertial mass and suspending it on a bed of helical coil springs. The choice of coil over pneumatic springs was motivated by:

1. The pneumatic spring system requires an automatic leveling system with a constant air supply. A coil spring design approach is passive and once leveled no further adjustments are needed.
2. The pneumatic springs require periodic maintenance. The coil springs are maintenance free.
3. Since pneumatic springs may require human intervention, the suspension pit must be designed and constructed to accommodate maintenance access. Since the coil springs do not require access, the building site design is simpler and construction costs less.

Because of the demanding vibration isolation ultimately required for this installation, a sequenced design-evaluation-redesign process was implemented. The steps and outcomes are presented in the following sections.

Lumped-Mass Simulation Feasibility Evaluation

A feasibility study was initially performed with lumped-

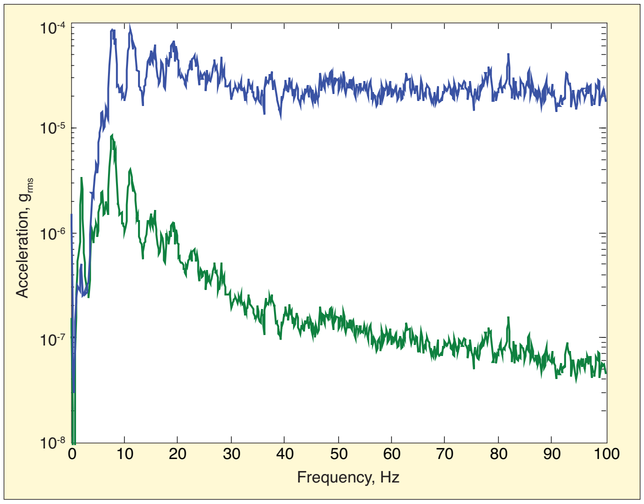

Figure 5. Averaged vertical acceleration spectra for the ground vibration (blue) and the two-degree-of-freedom, lumped-mass isolation system model (green).

mass model analyses. The objectives were to capture the macroscale dynamic behavior sufficiently to access if the required vibration isolation could be achieved for the actual environmental site conditions. Of particular concern was the isolation capability of the high-amplitude transient events contained in the train ground vibration. The models considered only the vertical motion so they could be developed and the simulations executed rapidly. The models were:

1. A single-degree-of-freedom model, with the only flexible component being the suspension stiffness.
2. A two-degree-of-freedom model that considered both the suspension and soil stiffness.

Since the models were developed with different assumptions, the predicted results could be examined from different viewpoints. Furthermore, because of the models' inherent simplicity and the significant uncertainty in some model parameters (soil stiffness), the evaluation focused only on establishing general performance trends.

The models were programmed with Simulink in the MATLAB® computing environment. The input to the models was the ground vibration recorded at the UPMC site for train pass-bys. Since the site acceleration (Figure 2) was measured, the corresponding velocity and displacement arrays needed in the model were estimated through numerical integration. Resulting suspended-floor model accelerations were analyzed using the spectral analysis methods discussed previously. A comparison of the ensemble-averaged spectra for the train ground vibration (Figure 2A1) and a model response is shown in Figure 5. The vibration isolation provided by the system is readily apparent. Close attention was paid to the effect on the peak vibration levels caused by the discrete transient events in the ground vibration. This was accomplished by examining the time histories and the STFT analysis.

Using the simulation models facilitated rapid parametric design studies to be performed to identify ranges of suitable system specifications that satisfied the isolation goals. The simulation results with a number of train ground vibration histories indicated that acceptable vibration isolation was achievable within a reasonable range of system design parameters. The parameter range was viewed as being an especially critical outcome from the simulations. The ranges indicted that robust design solutions were feasible even in light of the inherent uncertainty of many the model parameters. The simulation results were encouraging enough to proceed to the next design/evaluation step.

Subscale Isolation Test Floor

Aside from the lumped-mass models' simplicity, a number of unquantifiable uncertainties existed in the model parameters and the ground vibration inputs.

Figure 6. Subscale vibration isolation test floor.

1. During construction of the UPMC Sports Performance Center, large quantities of fill were used to make the former steel mill a suitable building site. The mixed fill creates variable and unpredictable soil stiffness throughout the construction site. The soil dynamic characteristics can significantly affect predictive accuracy of the modeling.
2. The vibration excitation characteristics of each train are different, depending on speed, weight, type of rolling stock (coal, tanker, container, or car carrier, for example), wheel condition, etc. The excitation variability creates uncertainty in the input used for the dynamic simulation results.
3. The ground motion excitation was assumed to be one dimensional. The actual particle ground motion can be very complex (either prograde or retrograde elliptical particle motion from Rayleigh waves) and is not taken into consideration.
4. The coherent and incoherent ground excitation effects from the spatial spring distribution are not captured by the single-spring lumped system.

The combination of simplicity and uncertainty in the lumped-mass modeling casts doubt on the accuracy of the simulation results. The task quantifying the model parameters with sufficient accuracy was difficult, if not impossible. Therefore, more sophisticated modeling was not deemed capable of providing results with a very high level of confidence due to the inherent uncertainties. Therefore, a subscale test floor was constructed at the UPMC site adjacent to the actual proposed MRI installation location. The subscale model provides the ability to more accurately evaluate actual achievable isolation.

The test floor was an 8 × 8 × 1 ft reinforced concrete slab supported by four helical coil springs from Mason Industries at each corner on 6 ft centers .[9] Careful attention was paid to specify springs having similar stiffness values both vertically and horizontally. This created lateral stability for the floor and caused the natural frequencies for the other rigid body modes to be similar. The springs rested on a foundation consisting of a 6-in. concrete slab with 18-in. footers around the perimeter. A vertical PVC pipe was cast into the floor to allow instrumentation access to the foundation slab. A photograph of the subscale test floor is shown in Figure 6.

Impact tests were performed with an instrumented sledge hammer (PCB 086D50) to identify the floor's resonant frequencies. The tests confirmed that the design vertical natural frequency of approximately 2 Hz was obtained. The impact tests were also used to identify elastic modal frequencies in the concrete floor.

Train pass-by vibration data were acquired and processed with seismic accelerometers (PCB393A03) placed on the foundation and floor concrete slabs. The respective acceleration responses were recorded and analyzed for a number of trains. Comparison of a typical foundation and isolated floor spectra from 0-100 Hz is shown in Figure 7. The achievable low-frequency vibration attenuation is clearly apparent. Significant

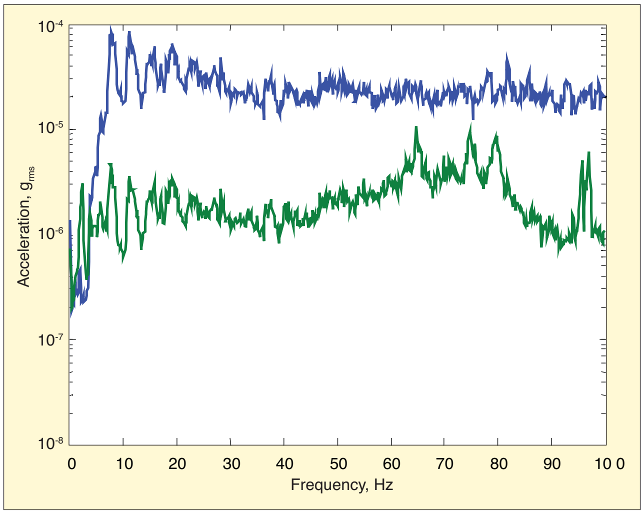

Figure 7. Acceleration spectra for train pass-by from the foundation (blue) and subscale vibration isolation test floor (green).

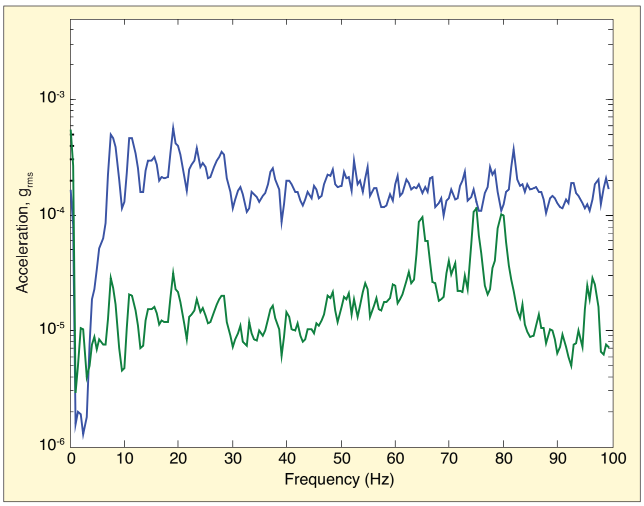

Figure 8. Maximum acceleration spectral bin site compliance spectra for the for a train pass-by from the foundation (blue) and the subscale vibration isolation test floor (green).

attenuation is obtained below 50 Hz. However, from 50-100 Hz, the attenuation is less. The maximum spectral bin MRI site compliance analysis with a 90% overlap is shown in Figure 8. Again, significant isolation is apparent below 50 Hz but not in the higher 60-80 Hz frequency range. The degradation of the isolation obtained in the higher frequencies was a surprising outcome, since it violates basic vibration theory and warranted further examination to determine the root cause.

The STFT analysis of the floor response is shown in Figure 9 and provides insight into the unexpected isolation outcome. Note the high-level response occurring in the 60-80 Hz frequency range at the beginning of the train pass-by. The time localization indicates that the event coincides with the locomotive passing. It is this event that is causing both the ensemble average spectra (Figure 7) and site compliance analysis (Figure 8) to show the higher-level response in the 60-80 Hz frequency range.

Further testing was performed on the vibration response in conjunction with microphone signals. The analysis showed that the high-amplitude floor response between 60-80 Hz was caused by acoustic radiation from the locomotive. Therefore, the transmission path was airborne and not through the ground. Figure 6 shows that there is a direct line of sight between the locomotive and the test floor, providing an unobstructed acoustic path. The actual MRI isolation system installation will be fully enclosed within the building, so the direct airborne path will be broken. However, the airborne excitation is still a concern because of the relatively lower noise transmission losses

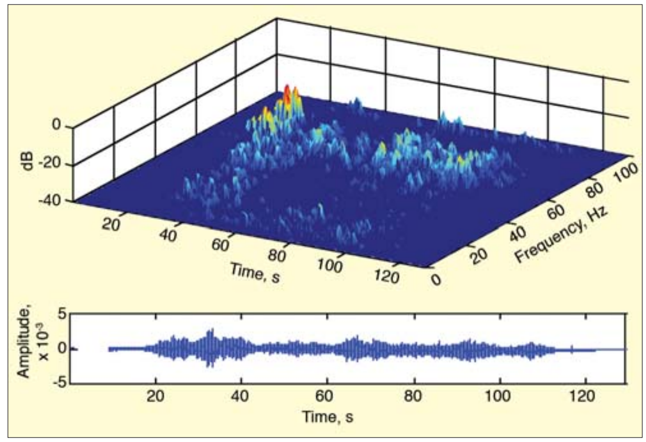

Figure 9. STFT of acceleration for train pass-by from the subscale vibration isolation test floor.

achievable in this frequency range. So it is plausible that the MRI suspension floor vibration will also experience some response from the noise emitted by the locomotive.

The environmental ground vibration shown in Figure 3 was recorded for the same train pass-by analyzed in Figure 9. So a direct comparison of the floor input and response is possible. The STFT analysis provides additional insight into the isolation performance. The highest amplitude ground vibration occurs between 5 and 50 Hz. Figure 3 shows that significant ground excitation in the 5-20 Hz range for the entire train passage. The measured subscale floor response in Figure 9 shows that this frequency content is obliterated. Further, all the ground vibration transient events are isolated very well by the suspension. Some artifacts of the transient events are apparent in the 60-80 Hz range. The excitation and transmission path source was traced to airborne noise created by the rolling stock wheel rail interaction.

The measured transmissibility and coherence function between the foundation and suspended floor vibration signals is shown in Figure 10. For comparison purposes, the theoretical transmissibility for a single-degree-of-freedom system is also shown. The coherence shows a high-quality measurement obtained between 5 - 30 Hz. Above 30 Hz, the coherence starts to degrade due to the natural attenuation of the floor suspension and the influence of the uncorrelated airborne excitation above 60 Hz. The transmissibility function shows significant deviation from theory illustrating the effects of unpredictable phenomena on actual system performance. In the 5-30 Hz range, the measured transmissibility was approximately 0.08.

The subscale tests were highly successful and provided invaluable information to guide the design of the actual MRI isolation system.

- `It demonstrated that the helical-coil spring concept could provide the necessary vibration isolation needed to satisfy MRI site compliance specifications.
- The suspension produced a transmissibility of approximately 0.08 from 10-40 Hz.
- The suspension provided adequate isolation of the high-amplitude transient ground vibration.
- The presence of rigid-body floor modes other than vertical did not adversely affect transmissibility.
- The measured transmissibility showed the limitations of using basic vibration isolation theory to predict performance. Unforeseen effects such as additional acoustic transmission paths and other physical effects cause the deviation from idealized predictions. So theoretical predictions should be viewed as the best possible achievable results. The expected deviation from the theory can be evaluated from an experiential basis by considering all the unique aspects of the site and design.

Ultimately the results from the subscale floor testing were assessed to bode well for probable success of full-scale implementation, and its construction proceeded.

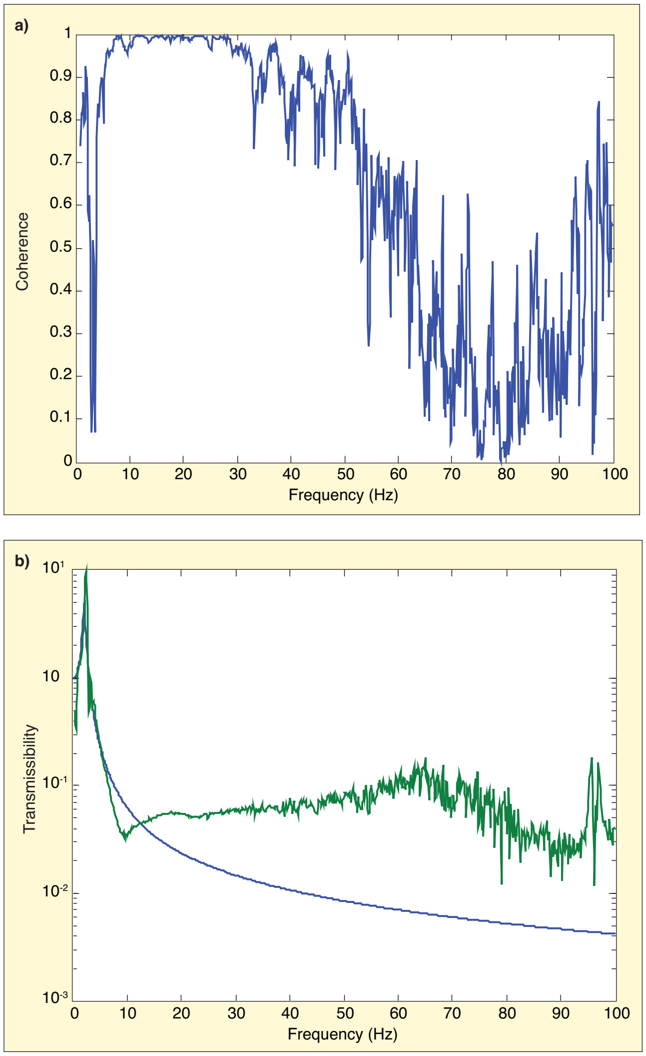

Figure 10. Coherence (a) and transmissibility (b) measured on the subscale isolation floor and the theoretical transmissibility for a SDOF model.

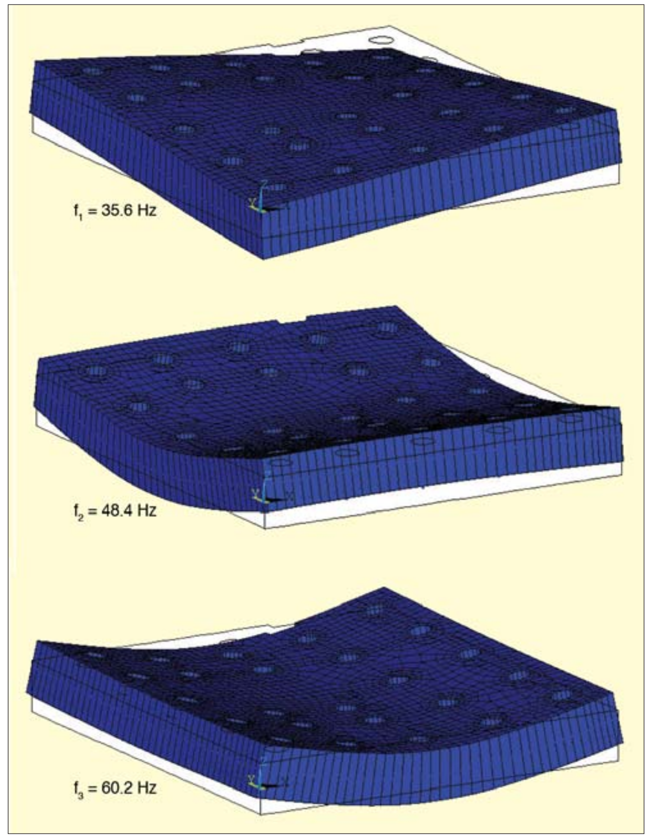

Figure 11. ANSYS finite-element analysis of the MRI reinforced-concrete floor.

MRI Room Vibration Isolation Design

The MRI isolation system was designed to place the entire examination room on a suspended inertial mass. The floor area was a rectangle of about 22 × 20 ft. The room walls, ceiling, and MRI were to be placed on a thick reinforced concrete floor supported by a bed of coil springs. The entire room was encased in multiple layers of steel and copper sheeting to shield the MRI magnetic field from interference caused by trains passing nearby.

The floor suspension consisted of an array of 25 Mason KI-138 spring mounts.[9] Springs were selected for 3 in. of static deflection. Each spring has a capacity of 8,300 lb and spring constant of 2,560 lb/in. The springs have an outside diameter of 7-3/4 in., a free height of 11 in., and a wire diameter close to 1-1/4 in. All springs were compression tested before shipment to confirm the spring constant. Due to magnetic field concerns, no mountings could be placed in a 78-3/4 in. box around the iso-center of the MRI. The springs themselves were supported on steel pipe stanchions that brought the springs close to the combined center of gravity of the inertial slab, MRI, surrounding room, and shielding. This limited the chance that the system would rock with any eccentrically imposed loads. The springs were deflected and the floor lifted by means of a three-bolt adjustment assembly built into the housing. The adjustment assembly included a down-stop that would limit the mount deflection in the unlikely event that the extreme-code live load was exceeded. The mounts are constructed to accept springs of various sizes and constants, so the mounts are 'tunable.' This provided a method of correction if the results did not meet those predicted by modeling, and allows the owner to change the mountings if they update a system with a heavier or lighter MRI in the future.

A finite-element analysis was performed on the reinforced concrete inertial floor to establish the desired thickness and evaluate if the elastic resonances may adversely affect MRI operation. The modeling and analysis was performed using ANSYS. The model included the rebar pattern and the empty cylinders cast into the concrete slab for installation of the springs. A parametric study was first performed to calculate the natural frequencies as a function of floor thickness. Ideally, it would be desirable for all the elastic frequencies to be above 100 Hz. From a practical design point of view, however, it was impossible to achieve. The analysis resulted in selecting a slab thickness of 30 in.. The first three natural frequencies were computed to be 35.6, 48.4, and 60.2 Hz. The corresponding mode shapes are shown in Figure 11. The design will have to be sufficiently tolerant of these resonant frequencies, since they are in a range that potentially could produce troublesome vibration if dynamically excited. Examining the first mode shapes shows that the largest deformations occur at the corners, with little vertical motion near the center. The MRI is to be placed near the center, so if this mode were to be excited, the dynamic movement would be expected to be minimal. However, modes 2 and 3 have the greatest elastic deformation in the center. Therefore, mode 2 at 48.4 Hz is the lowest resonant floor frequency that could potentially adversely affect the MRI site qualification. The subscale test floor indicated that significant ground isolation could be achieved in this frequency range. Furthermore, the slab bending stiffness is substantial, and the likelihood of the modal response being sufficiently large to affect the MRI was viewed as low.

Unfinished Floor Isolation Performance Evaluation

Approximately midway through the construction timeline, the vibration isolation performance was evaluated. Figure 12 depicts the construction state when tested. Note that a large plywood construction access door was located on an outer wall

Figure 12. Vibration isolated MRI room during constriction.

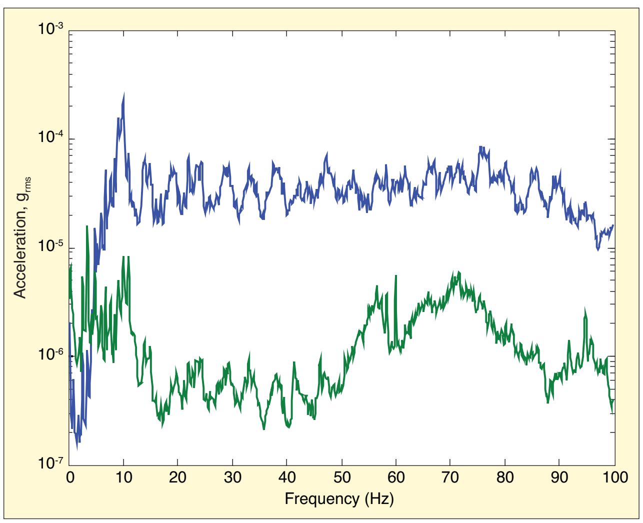

Figure 13. Averaged spectra for the foundation and the isolated MRI room under construction as seen in Figure 12.

that provided direct line of sight to the trains when open. The steel/copper cladding on the walls and the top access plates for the coil springs is apparent. At this point, the room was completely floating, with the only physical contact to the surrounding facilities being through the 25 coil springs. Five PVC pipes were cast in the floor slab to allow accelerometers to be placed on the foundation slab.

Impact testing was performed with an instrumented sledge hammer. The tests confirmed whether the suspension frequencies and the elastic resonant frequencies in the 30-inch concrete floor were accurate. The rigid body suspension natural frequencies were in the 2-3 Hz range with very low damping. The light damping caused a ring-down of approximately 30 sec before the vibration decayed to acceptable values for the MRI when a person walked onto the floor. The elastic resonant frequencies in the floor were within 2 Hz of the finite-element values for the critical first three modes.

The same data acquisition and processing procedures were applied to numerous train pass-bys. Averaged spectra for the foundation and floor are shown in Figure 13. The isolation below 50 Hz is apparent, but there was higher than expected vibration in the 60-80 Hz region. This phenomenon was also

Figure 14. Vibration isolated MRI room nearing construction completion.

experienced with the subscale test floor. During testing, the construction access door was open to provide an unobstructed airborne acoustic transmission path. Acoustic tests confirmed that in the 60-80 Hz region, the floor responds to the locomotive and rolling stock sound radiation.

Direct measurement of the transmissibility between accelerometers on the foundation and floor proved problematic. The coherence function was considerably more erratic than the subscale model results in Figure 10. The poorer coherence function raised questions about confidence level in the measured transmissibility. Since the floor is mounted on 25 springs, each one provides a unique transmission path between the ground and floor. The ground vibration from the moving train is also spatially distributed, creating somewhat different inputs at the base of each spring. So the floor is actually responding to 25 partially coherent input forces. One accelerometer could not adequately characterize the input and caused a reduction in transmissibility function quality. Therefore, the transmissibility was evaluated through the ratio of the spectra in Figure 13 and the measured transmissibility function. The transmissibility was estimated as a relatively constant value of $t_r = 0.05$ across a frequency range of 10-50 Hz.

Site qualification evaluation results using the maximum sliding window analysis showed the performance to be excellent. The isolated floor easily satisfied the MRI manufacturer's vibration qualification criteria.

Finished Room Evaluation

After the MRI was installed and the examination room was nearing completion, site vibration tests were again performed. The almost finished construction can be seen in Figure 14. At this point, the construction access door was removed and replaced with a solid wall. All mechanical utility connections (HVAC, electrical, magnet cooling supply) between the stationary surroundings and the suspended room were installed. All connections were designed and constructed to be as flexible as possible so not to create additional vibration transmission paths or restrict the free movement of the suspended room.

Impact tests were again performed to identify the natural frequencies with the 10,000-lb magnet and all the utility connections installed. The rigid-body room modes remained in the 2-3 Hz range. However, a significant change occurred in the damping. The mechanical connections raised the damping so that the response from human walking now decayed in several seconds. While this is beneficial from an operations point of view, the increased damping can adversely affect transmissibility.

Vibration train pass-by tests were again performed. Direct measurement of transmissibility was again problematic, and isolation performance was best evaluated through comparing foundation and floor response spectra. Typical ground and room response spectra are shown in Figure 15. The results illustrate that significant vibration isolation has been obtained over the entire frequency range. Of particular note are two frequency regions that deviate from the previous unfinished floor results:

1. There is decrease in vibration isolation performance in the 10-20 Hz region. The change is attributed to the increased damping from the utility connections to the surroundings.
2. A reduction in the room vibration response in the 60-80 Hz range is also observed. This is attributed to the degradation of the acoustic transmission path from completion of the exterior walls surrounding the suspended room. It has not been fully eliminated, but significantly reduced.

A dramatic depiction of the performance achieved by the isolation system design is provided by the STFT analysis of the ground and floor responses shown in Figure 16. For this particular train passage, there are a high number of transient events creating a very active ground vibration environment. The suspension system very effectively isolates the MRI room from all the ground vibration.

Vibration compliance tests for multiple train passages were performed. The facility readily satisfied the manufacturer's criteria for all trains. The final design and construction was successful.

Summary

Developing a vibration isolation system for a MRI site 50 ft from a busy heavy freight rail line has been discussed. The severe ground vibration caused by the rail traffic created very demanding performance needs for the isolation system. Because of the severe environmental conditions, a successful outcome was by no means assured. Therefore, a sequenced development process was adopted, where comprehensive analysis and testing could constantly guide the detail design. In this manner, the continuous design refinement helped maximize isolation performance.

Because of the severity and characteristics of the train-induced ground vibration, the data evaluation processes were tailored to meet the needs of the application. The ground vibration was a mixture of continuous stationary type signals with occasional high-level discrete transient events. The site qualification criterion data processing employed a "sliding window" algorithm to capture the effects of all critical events in the evaluation. This algorithm assured that the site qualification criterion would be evaluated in the strictest sense and prevents a "true-negative" assessment. In addition to traditional spectral analysis methods, the short-time Fourier transform provided invaluable insight into time-localized effects caused by the locomotive and/or rolling stock wheel-rail interaction.

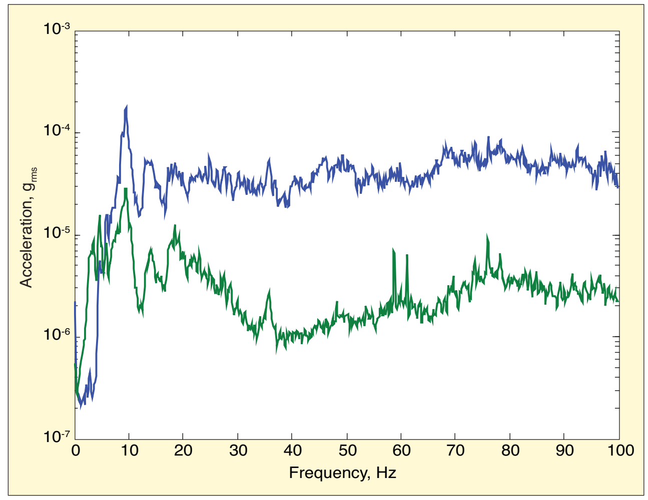

Figure 15. Averaged acceleration spectra for a train pass-by from the foundation and the isolated MRI room nearing completion as seen in Figure 14.

Evaluating the subscale test floor and the MRI examination room at two states of construction showed that simple lumped-mass vibration isolation theory provides an overly optimistic performance estimate. A number of practical issues affect actual achievable isolation; they are not captured by basic theory, including:

1. Multiple partially coherent ground motion inputs to the support springs.
2. Acoustic transmission paths.
3. Utility connection transmission paths.
4. Elastic resonances in the room and inertial floor among other more subtle effects.

Accurate prediction of performance is difficult; any apriori performance evaluation must consider:

1. Unique aspects of each construction site.
2. Characteristics of the ground vibration environment.
3. Careful consideration of many unobvious and unquantifiable aspects from an experiential point of view.

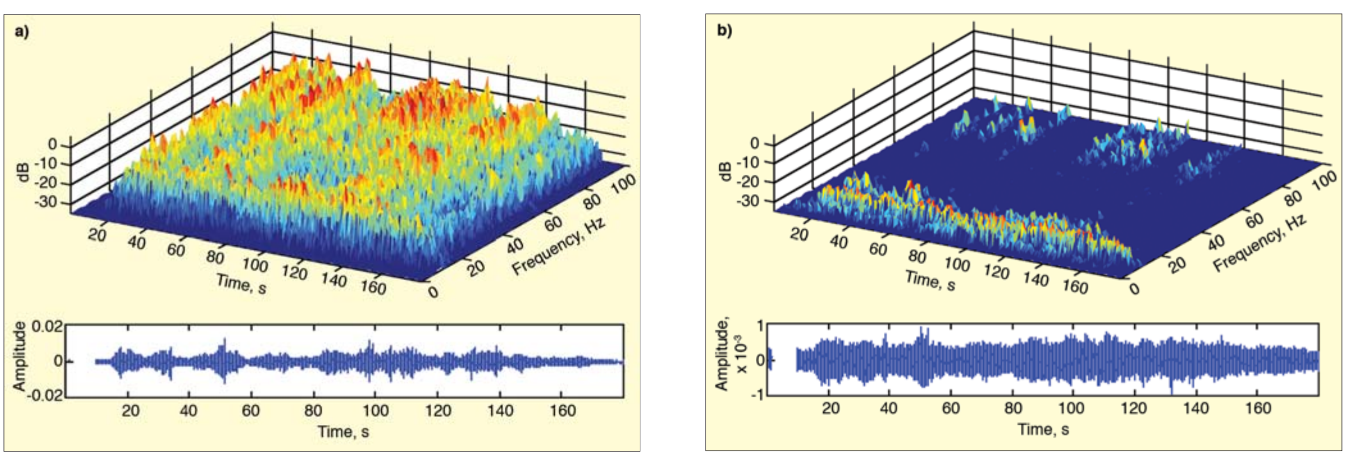

Figure 16. STFT analysis of the foundation and nearly completed isolated MRI room accelerations for a train pass-by.

Construction materials and methods can adversely affect the achievable isolation performance. Interaction with the contractor throughout construction is important. Periodic and thorough inspection of the site by a vibration specialist is critical to ensuring the isolation performance is not compromised during construction.

Ultimately the design and construction of the vibration isolation system for the UPMC Sports Performance Center was highly successful. Since, the new MRI started operation in late 2005, there have been no schedule disruptions caused by the frequent nearby train traffic. Even more importantly, the MRI image quality was high. This serves as an example of how with careful design, analysis, testing, and construction that sensitive medical equipment can be sufficiently isolated to operate in a severe vibration environment.

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