Designing Vibration-Sensitive Facilities Near Rail Lines

Ramon E. Nugent, Acentech Inc., Westlake Village, California
Jeffrey A. Zapfe, Acentech Inc., Cambridge, Massachusetts

Vibration is one of the most significant challenges building designers face when locating sensitive facilities and equipment near rail lines. This issue has become even more important with recent advances in nanotechnology research, particularly at universities in busy urban settings. Here we discuss some of the considerations related to vibration-sensitive facilities near rail lines. Two case studies will be presented that cover vibration prediction and how the vibrations are affected by the presence of the building. A third case study is used to show how high-performance supplemental vibration isolation systems can be used to mitigate vibration exposure to an NMR facility.

Sensitive research operations often require facilities with very low levels of floor vibration. When siting new buildings, finding acceptably "quiet" locations can be challenging, particularly if the institution is located in a busy urban setting. Of the various potential sources of environmental vibration, railway lines tend to be the ones that produce the most vibration. When circumstances find sensitive facilities and rail lines in close proximity, the facility developer is presented with the challenge of devising a building design and/or mitigation strategy to keep the vibration disturbances within acceptable limits. This article presents data from three case studies that discuss considerations for new buildings near rail lines, how the vibrations from rail systems are affected by the presence of the building and what additional steps can be taken to provide enhanced mitigation.

Vibration Criteria

Early on in a project, the design team often does not know what specific equipment will be housed in a completed building. To help the design process, in the 1980s researchers at Bolt Beranek and Newman developed a set of curves to define classes of vibration-sensitive equipment.[1] The generic vibration criteria (VC) curves are still widely used today to design vibration-sensitive facilities. The VC curves are currently referenced in the noise and vibration assessment guidelines published by the Federal Transit Administration and the Federal Rail Administration.[2,3] Figure 1 shows the common family of VC curves. The generic criteria are frequency dependent and extend from 4 cycles per second to 80 cycles per second.

The VC level is defined by the flat section of the curve. The curves are less stringent at low frequencies, because most instruments behave like rigid bodies at low frequencies, producing little relative motion between components (a mirror and a laser for example).

VC-A (2,000 µin/s) is appropriate for general labs where people use bench-top microscopes and balances. VC-A is generally also used for vivariums, although vibration effects on animals are not well understood. As a point of reference, the human perception threshold ranges from 4,000 µin/s to 8,000 µin/s, so in most cases, sensitive instrument criteria correspond to vibrations that cannot be felt by people.

Most manufacturers of sensitive equipment have very detailed and specific vibration criteria that are not always expressed in terms of vibration velocity like the VC curves. Acceleration is a common metric for magnetic-resonance imagers (MRIs), and displacement is common for electron microscopes. Often instruments are more sensitive to vibration at some frequencies than others, and the criteria will reflect these differences.

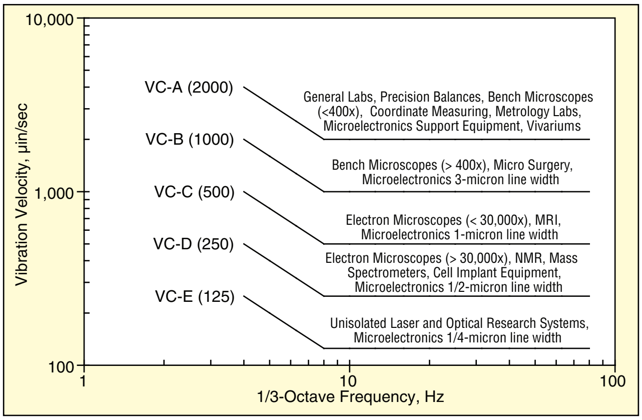

Figure 1. Generic vibration criteria.

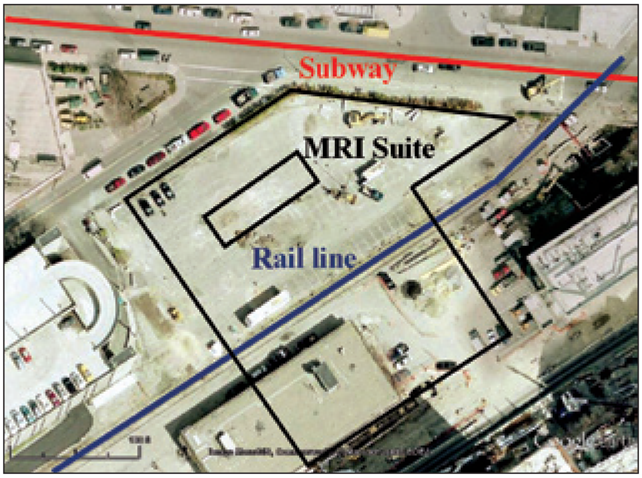

Figure 2. Case Study 1: Overview.

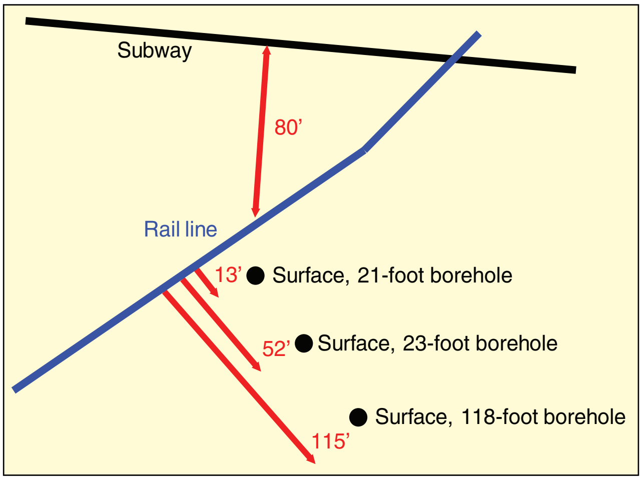

Figure 3. Case Study 1: Measurement layout.

Case 1 – MRI Facility near Freight Line

Figure 2 illustrates the challenges of locating a vibration-sensitive facility in a busy urban environment. This was a new building that was located near a busy street, a subway line and a rail line

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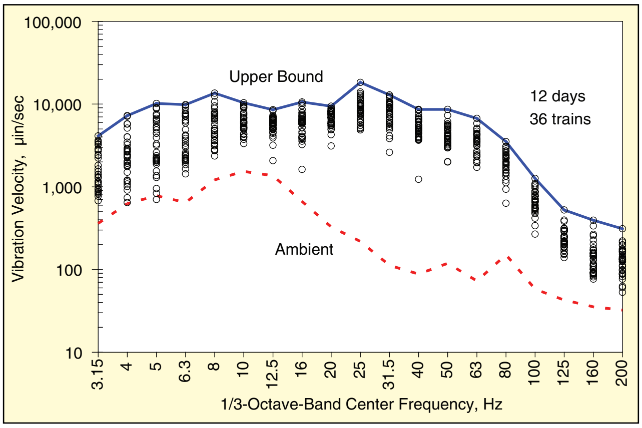

Figure 4. Case Study 1: Surface spectra at 52 feet.

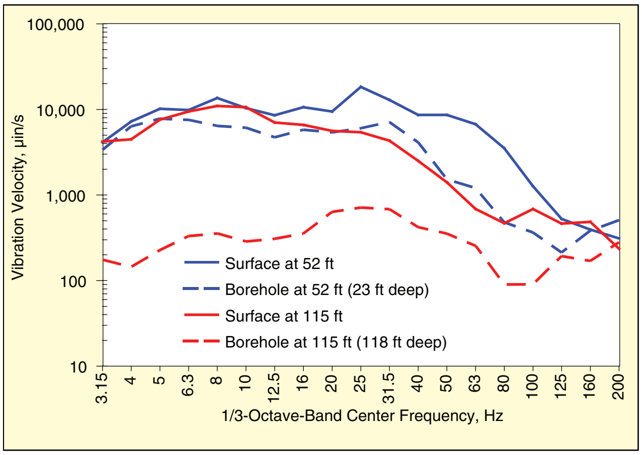

Figure 5. Case Study 1: Surface and borehole spectra.

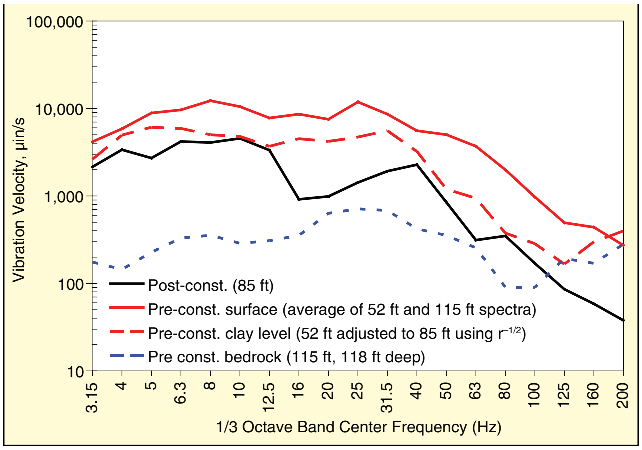

Figure 6. Case Study 1 Pre- and post-construction vibration spectra.

that carried one or two trains per day. Our client wanted to locate a research building here that would contain, among other things, a vibration-sensitive MRI suite on the ground floor. Although not obvious from the photo, this was a rather extreme case, where the north and south sections of the building formed a tunnel that the rail line passed through.

The design process for the new building began with a measurement program to quantify the train-induced vibration levels at the site. The vibrations were measured on the ground surface and in boreholes drilled to the approximate depth of the foundation systems that were under consideration.

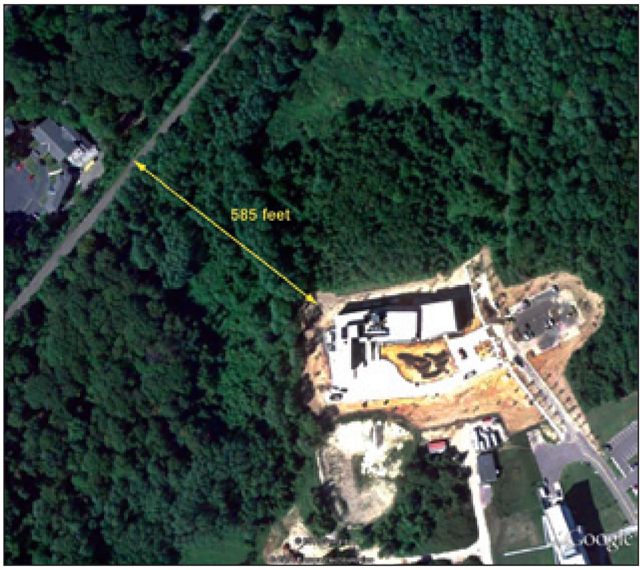

Figure 7. Case Study 2: Overview.

A line of surface vibration sensors were set up at 13, 52, and 118 feet from the tracks, as shown in Figure 3. At the time of the measurements, the foundation design had not yet been decided. To measure the vibrations at depth, three boreholes were drilled next to the surface sensors. The first 20 feet of soil or so was glacial till. This was followed by a clay layer that continued down to the bedrock. The depth of the bedrock varied from 65 to 135 feet deep. The first two boreholes were drilled just into the clay layer at 20 ft; the third went all the way down to bedrock at about 118 feet.

The principal vibration source at the site was a diesel locomotive pulling freight cars at about 15 mph. The train schedule was very unpredictable, so we set up a digital tape recorder with a level trigger to record train events. Over 12 days of measurements, we measured the vibrations from 36 trains. Figure 4 shows the pass-by maximum vibration spectra that were measured on the surface 52 feet from the tracks. As indicated by the spread shown by the black circles, there was considerable variation in the train vibration levels, especially at low frequencies. Because the researchers indicated that even short events could disturb their experiments, we used an upper-bound spectrum to characterize the vibrations. The maximum levels were on the order of 10,000 µin/s, which is high even for a general lab space.

The curves in Figure 5 show the upper-bound spectra measured on the surface and in the boreholes at 52 and 115 feet from the tracks. The surface spectra (solid lines) showed modest attenuation with distance at low frequency, as would be expected. The vibrations in the boreholes were generally lower than the surface. At the 52-foot sensor position, the vibration levels in the 23-foot borehole were only about half as severe as the surface. On the other hand, vibrations on bedrock were considerably lower (about 20 dB) even at low frequencies.

Because the levels at 23 feet were not that much lower than the surface, there seemed to be no compelling vibration-related reason to design the building with a basement. And while the bedrock performance was impressive, there was a real concern that this could not be effectively exploited, since piles to bedrock would have soil contact all along their length, which would detract from the benefits of the direct bedrock support.

With the somewhat limited mitigation expected from the foundation system, the projected levels in the completed building were a concern, because they exceeded the criterion for the planned MRI. The question was whether or not the researchers could deal with the disruption two to three times per day.

After weighing their options, the client opted to proceed with a flexible design. They used a mat foundation supported by piles to bedrock. They also designed a pit in the MRI suite that could be used to house an isolation system (if necessary). The plan was to re-measure the vibrations in the pit once it was completed and to either install an isolation system if it was needed, or fill the bathtub with sand topped with concrete if isolation was not needed. In the end, the pit was filled and topped because the MRI system that was ultimately selected had its own isolation system that offered sufficient protection.

Having measured the vibrations in the pit, we were able to compare them to the vibrations measured at the site before construction. Figure 6 shows the vibration spectra that were measured in the isolation pit. In the final design, the MRI was located about 85 feet from the tracks and was essentially at grade. Since we did not measure at exactly 85 feet before construction, we extrapolated the pre-construction spectra from 52 and 115 feet; this is also shown on Figure 6. As the figure shows, the vibrations in the completed building were only about half as severe as the vibrations measured on the surface before construction. So despite the presence of the rather massive building, the low-frequency vibrations associated with the train were not dramatically different than they were on the green field site before the building was constructed.

Case 2 – Research Facility near Commuter Rail Line

A vibration-sensitive facility is located about 585 feet from a commuter rail line (see Figure 7). The sensitive areas are located on a grade-supported slab at ground level. The building was far enough from the rail line that vibration was not a significant concern. In this case, we were fortunate to have the opportunity to measure the train-induced vibrations in the completed building which we could then compare to the vibrations at the site before construction.

Figure 8 shows the vibration spectra that were measured at the site before and after the building was constructed. In both instances the greatest train-induced vibrations occurred between 6.3 and 40 Hz and were about 10 times higher than the ambient vibrations. Even at a distance of 585 feet, the greatest train-related vibrations here amounted to about 800 µin/s before construction. After construction, the train-related vibrations were about half as severe but still exceeded 300 µin/s.

Unfortunately we didn't have a reference location near the rail line, so we do not know how the condition of the rails and rolling stock might have changed between the two measurements, which were about three years apart. Even so, the pre- and post-construction vibrations were quite similar, indicating the presence of the building did not have a dramatic effect in suppressing low-frequency vibration.

Case 3 – Vibration Mitigation for NMR near Freight Line

This case involved a nuclear magnetic resonance (NMR) facility, where the NMRs were to be located in the basement of a research building about 350 feet from a busy freight rail line. Figure 9 shows the relative position of the facility to the rail line. Measurements in the building early on in the construction process showed that the vibrations from freight trains would exceed the instrument's criterion. We were asked to help design a mitigation system for two of the NMRs in the building.

In designing supplemental vibration mitigation, one must always be mindful of the fact that most pieces of sensitive equipment have their own internal isolation systems. Stability issues can arise if one soft spring is simply stacked on top of another soft spring without a large intermediate mass between the two isolation systems. The intermediate mass, commonly referred to as an inertia block, serves to dynamically separate the two isolation systems which means they can effectively be treated as two dynamically independent isolation systems. As a rule of thumb, the inertia block should be 10 times the mass of the isolated payload (the isolated portion of the sensitive equipment).

Inertia blocks are often recessed into the floor and are difficult to see once they are installed. We were fortunate to have a recent project where this wasn't the case. This project required a very large block (80,000 lb), and it had a large open area under the floor where the block could be easily seen. Figures 10 and 11 show photos of this inertia block system (from below and above the floor, respectively). The block is "T-shaped" to keep the vertical center of gravity at the top of the isolators; this helps reduce vertical-horizontal coupling (horizontal motion produces rocking motion). The eight isolators are air-springs with a natural frequency of about 1.5 Hz. A half-inch air gap separates the block from the rest of the building floor.

Figure 12 shows how the NMR isolation system performed. The red line shows the vibration on the floor next to the block. This clearly exceeded the NMR's criterion. The black line shows the vibration on the block, which was well within the criterion limits.

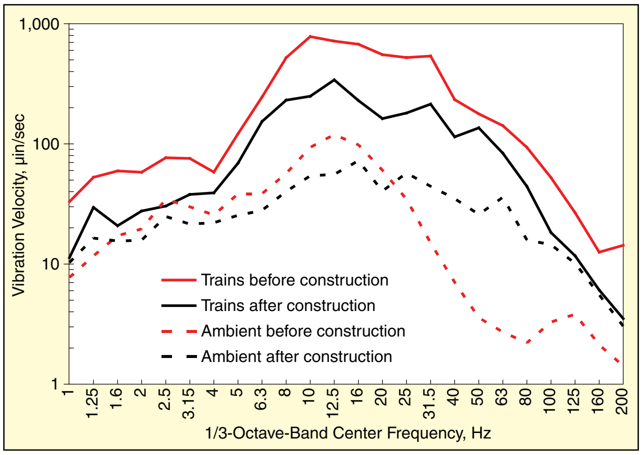

Figure 8. Case Study 2: Vibration spectra before and after construction.

Figure 9. Case Study 3: Overview.

Figure 10. Case Study 3: Air-spring-supported inertia block.

As with all passive vibration isolation systems, there was a slight amplification at the resonance of the isolator. Amplification is usually not a problem, since there is typically only minimal vibration energy at low frequencies to begin with.

Conclusions

In many cases, vibration-sensitive facilities can be built near operating rail lines if proper design considerations are implemented. These considerations include field vibration measurements to

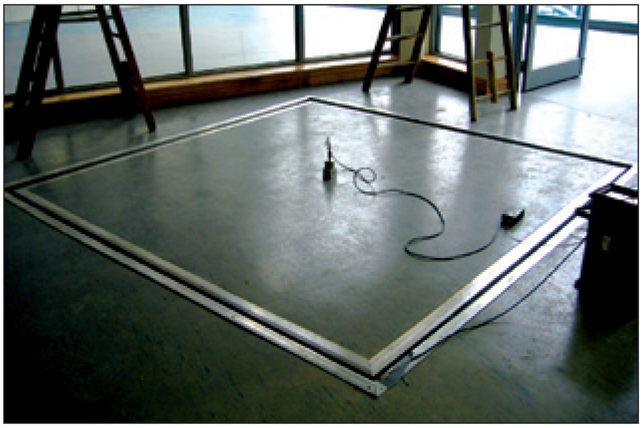

Figure 11. Case Study 3: Top of inertia block.

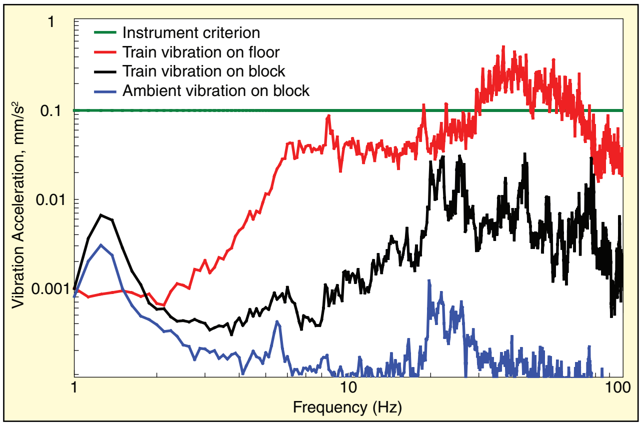

Figure 12. Case Study 3: Inertia block performance.

determine levels of vibration at the surface and below grade as appropriate, allowance for building suppression effects, and local vibration mitigation.

While the presence of the building certainly does affect the vibrations at the site, at low frequencies where vibrations from rail systems are most severe, the reductions can be modest. In two instances where we were able to measure the vibrations before and after construction, the low-frequency vibrations from rail traffic were only about 50% lower.

References

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The authors can be reached at: jzapfe@acentech.com.