In-Service Tests of the Effectiveness of Vibration Control Measures on the BART Rail Transit System

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Abstract

This paper presents results of a number of vibration measurements of the different track forms used on the current San Francisco Bay Area Rapid Transit (BART) system including floating slab, resiliently supported half ties and high-resilience direct fixation fasteners in subway and one section of floating slab used on at-grade track. The goal was obtain data that would improve the predictions of future vibration levels and perhaps lead to more cost effective vibration mitigation strategies for the proposed BART extension to San Jose. The tests show that the floating slabs are performing much as designed, the resiliently supported half ties are less effective than expected, and the high resilience track fasteners are probably performing as expected although the results are clouded because of severe rail corrugation in the area where the new fasteners were installed. One unanticipated result is the apparent interaction of the floating slab resonance, the wheel rotation frequency, the bogey dynamics, and vibration propagation characteristics of the ground.

1. Introduction

The Bay Area Rapid Transit (BART) System is an approximately 75 mile long rail rapid transit system linking most cities in the San Francisco Bay area. The Silicon Valley Rapid Transit Project (SVRT) is a proposed extension of the system to San Jose. The SVRT project is currently completing the environmental review process and moving into the Preliminary Engineering phase. The preferred alignment for the extension passes in close proximity to a number of residences. As a result, substantial mitigation will be required to ensure that noise and vibration from train operations will not exceed the standards used for the environmental assessment.

ATS Consulting and Wilson, Ihrig & Associates performed extensive measurements to characterize vibration on the existing system with the goal of developing strategies that would lead to acceptable noise and vibration levels at all sensitive receptors in the SVRT corridor. The vibration tests of the existing BART system that were performed for this study included:

- Hayward Test Track: A section of ballast and tie track at the BART Hayward Shops that is used to test vehicles. The track section is long enough that test trains can reach a speed of 65 mph.
- Concord floating slab: A section of at-grade floating slab track designed to have a fundamental vertical resonance of 8 Hz when a train is on the slab.[1] The floating slab is a discontinuous design with 6-foot sections supported by four natural rubber pads.

- San Francisco Airport (SFO) subway: The subway section of the recently completed extension of the BART system to SFO includes track sections with resiliently supported half ties (commonly referred to as LVT track), floating slab track, and direct fixation fasteners. Tests were performed at sections with all three track forms. The SFO floating slabs are continuous and are designed to have a vertical resonance frequency of 10 Hz.
- "Egg" high resilience track fasteners recently installed in an open cut section near the Balboa Park Station. BART has problems with rail corrugations in this area and retrofitted the northbound track with the Egg fasteners as a test to see if they would reduce the tendency for corrugations to form.

Vibration propagation tests were performed at all locations where train vibration was measured so that the effects of localized geology could be removed from that vibration data and valid comparisons could be made of the vibration benefits of the different track forms.

2. Test Procedures

A primary goal of the testing was to isolate the true insertion loss of each mitigation measure. This is always problematical because of the difficulty factoring out effects of localized geology on the measured levels of train vibration. The approach taken was to measure both train vibration and transfer mobility using an impact vibration force at each test site. The test configuration for at-grade track is shown in Fig. 1. A line vibration source was simulated by impacts at regular intervals parallel to the track centerline. Ground surface vibration velocity (vertical direction) was measured with a line of transducers perpendicular to the track. As indicated in Fig. 1, a similar series of tests were performed along the proposed SVRT corridor to measure transfer mobility from the track centerline into living spaces of adjacent residences. This procedure allows developing projected indoor vibration levels directly from the measurement results.

A similar test procedure was used for the subway test sections (Fig. 2) measuring transfer mobility from the subway invert to the ground surface. The measured point-source transfer mobilities for each line of impacts were combined to provide a line-source transfer mobility. For both the at-grade and subway tests we measured transfer mobility and train vibration using the same transducer locations. The vibration forces generated by the trains were then estimated using the following relationship for each 1/3 octave band:

$$FDL = L_V - LSTM \tag{1}$$

where L_V is the train vibration velocity level, $LSTM$ is the measured line source transfer mobility, and FDL is the force density. All are in decibels and a consistent set of decibel references is assumed. A separate FDL spectrum was calculated for each transducer location and average FDL was used to characterize the track type.
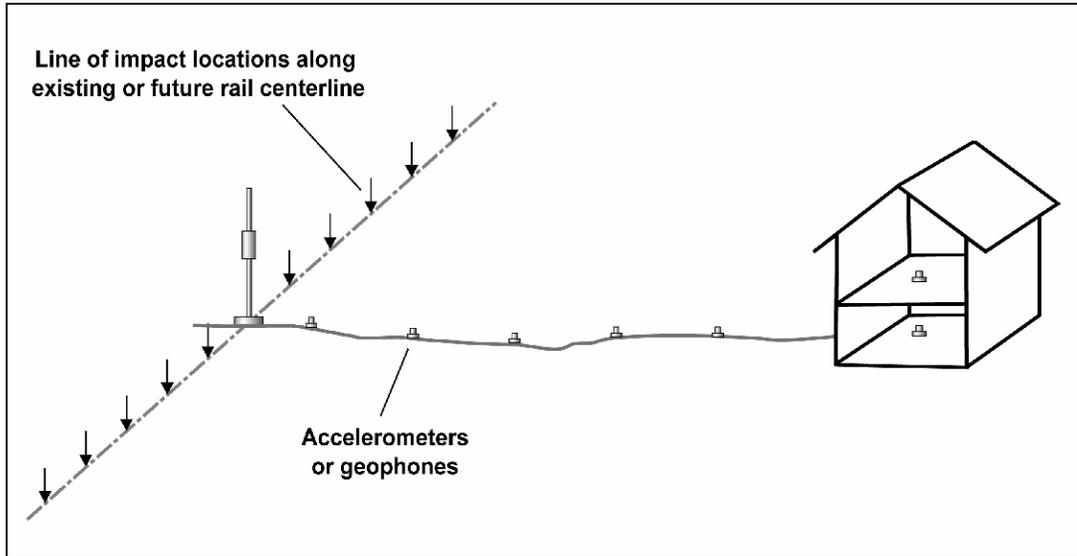
Fig. 1. Sketch of vibration propagation test procedure for at-grade track. As indicated in the sketch, additional tests were performed in the SVRT corridor from the proposed track centerline into living spaces of representative residences.
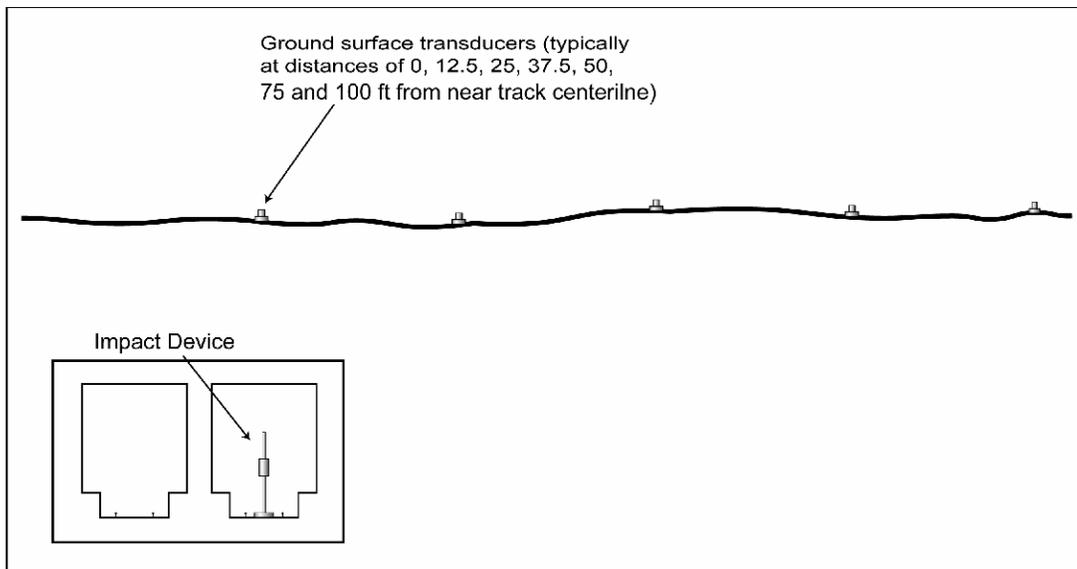

Fig. 2. Sketch of vibration propagation test procedure used for subway track sections. The measured transfer mobility is from the subway invert to the ground surface.

3. Measurement Results

3.1. At-Grade Track

The tests for at-grade track consisted at controlled speeds with a special test train at the Hayward Test Track and measurements of the revenue service trains at the Concord floating slab. Fig. 3 shows the average 1/3 octave band spectra for three similar distances measured from the track centerline at train speeds of 65 mph. This figure suggests that the floating slab track is dramatically reducing the vibration levels at frequencies of 16 Hz and higher.

Fig. 4 shows the line source transfer mobilities measured at the two sites. As is clear from Fig. 4, the two test sites have very different subsurface conditions which are partially responsible for the differences in train vibration. The transfer mobility at the Hayward Test Track site has much more high frequency content and less low frequency content than at the Concord site. Combining the train vibration from Fig. 3 and the transfer mobility from Fig. 4 gives the force densities in Fig. 5. The force density spectra shown in Fig. 5 are the average results from the seven measurement positions at each test site. The seven force density spectra curves from each test site were relatively tightly grouped and usually varied over a range 5 dB or less.

Note that the transfer mobility for the Hayward Test Track was measured from the toe of the ballast and for the Concord floating slab was measured from the concrete slab under the floating slab. This means that the concrete slab is incorporated into the transfer mobility at the floating test site.

The insertion loss for the Concord floating slab is shown in Fig. 6, where insertion loss is estimated as the difference in the average force densities. Because of the very low vibration levels for the floating slab measurements at frequencies above 40 to 50 Hz, we suspect that the curve in Fig. 6 understates the high-frequency insertion loss. Also, the positive insertion loss in the 6.3 and 8 Hz 1/3 octave bands results is suspect since one would expect it to be zero or negative due to the isolation system resonance. However, the minimum in the 10 Hz band may be attributable to the slab resonance. The overall conclusion is that the Concord floating slab is performing very well over a fairly broad frequency range.
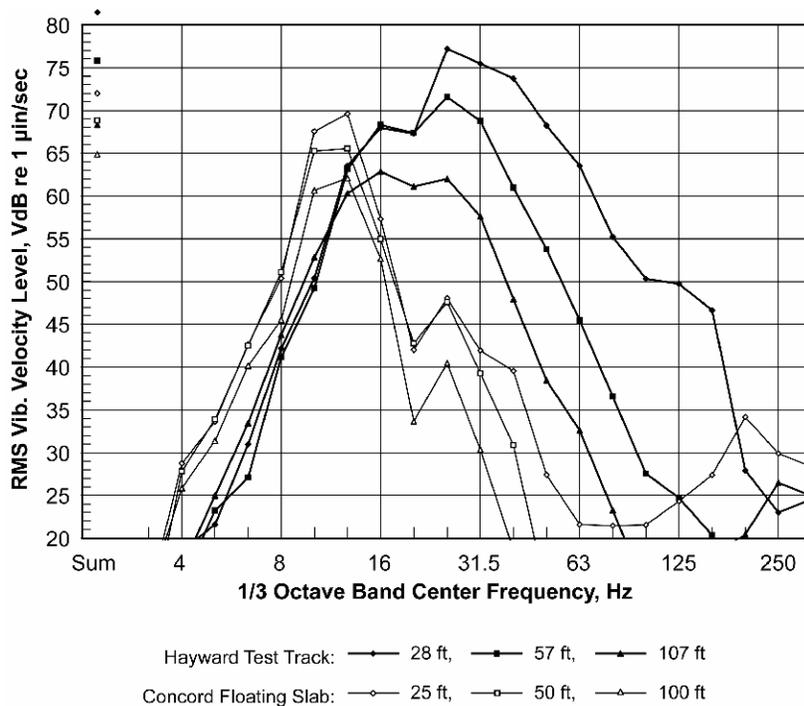

Fig. 3. Average vibration levels measured at Hayward Test Track and Concord floating slab. Average train speed was 65 mph at for both sites.
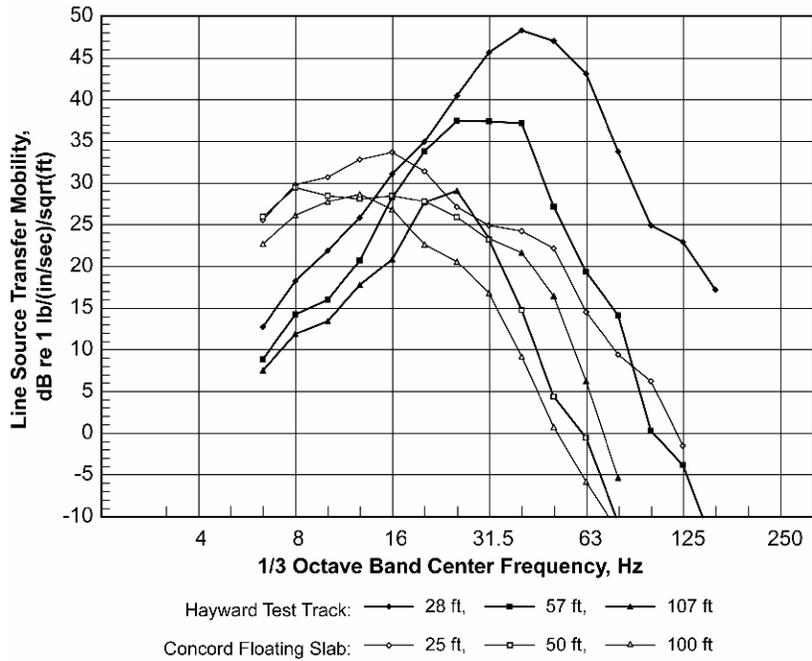
Fig. 4. Line source transfer mobilities measured at the Hayward test track and Concord floating slab test sites.
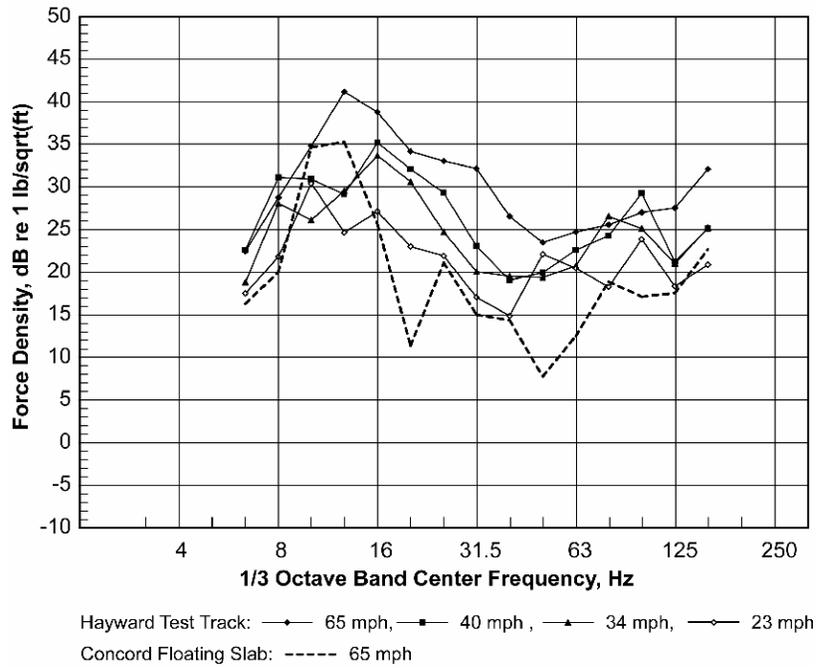

Fig. 5. Derived force densities for Hayward Test Track and Concord floating slab.
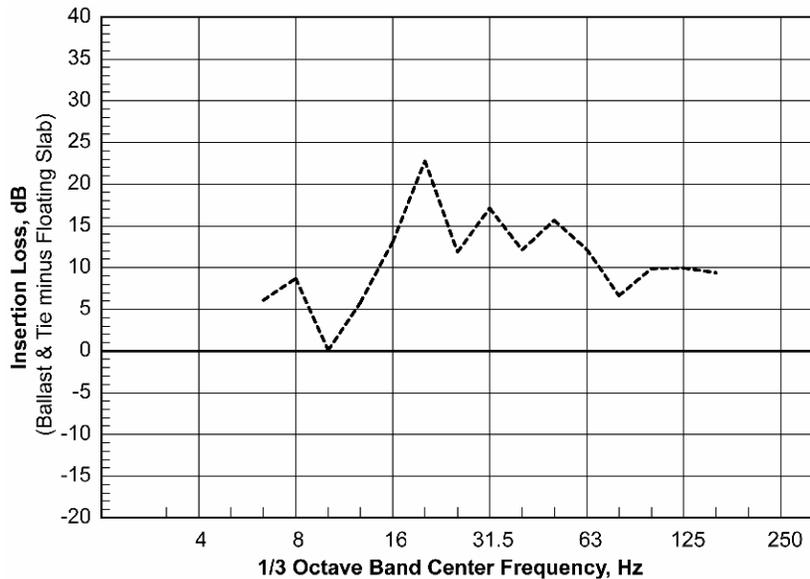
Fig. 6. Measured insertion loss for Concord floating slab compared to Hayward test track, 65 mph trains (positive insertion loss indicates improvement). The values at frequencies greater than about 40 to 50 Hz are questionable because of the low vibration amplitudes at the floating slab test site at these frequencies.

3.2. San Francisco Airport Extension Subway

The three SFO subway test sections were located within one mile of each other. The subway through this area is all double-box subway of cut-and-cover construction. The track is about 30 feet below the ground surface in the test area. The track forms used in the SFO subway are: direct fixation fasteners with a vertical stiffness of approximately 150k lb/inch, resiliently supported half ties (LVT track) with a similar track modulus as the direct fixation track, and continuous floating slab with a design vertical resonance frequency of 10 Hz. Fig. 7 is a photograph of the LVT track and Fig. 8 is a photograph of the floating slab section.

As discussed above and shown in Fig. 2, the intention was to use impact testing to measure transfer mobility from the subway invert to the ground surface at all three test sites in the SFO subway. Unfortunately, as shown in Fig. 8, the floating slab is a continuous design with no access to the invert large enough to perform impact tests. The means that we have to use a comparison of measured ground-surface vibration levels to infer how effective the floating slab is at reducing vibration levels.

Fig. 9 shows the vibration spectra measured at 25 and 100 feet from the track centerline (horizontal distance). The floating slab clearly has a dramatic effect (improvement) at frequencies greater than 16 Hz; however, because of the increased vibration energy at low-frequencies, the overall vibration levels are higher at the floating slab sections than at the direct fixation and LVT track sections. In looking at the vibration results at the floating slab section, we noticed that most of the trains either had a strong peak in the 10 Hz 1/3 octave band or the in the 12 Hz 1/3 octave band. We suspect that this peak is related to the wheel rotation frequency interacting with the floating slab resonance. Of a total of 11 trains, five were clearly in Group 1 (12 Hz) and four were clearly in Group 2 (10 Hz). There were two trains that did not fall into either group, possibly because of changing speeds as the trains passed the measurement site.

BART trains have 30 inch diameter wheels, which means that at 65 mph the wheel rotation frequency is 12 Hz. The programmed speed for trains in the test section of the SFO subway is 65 mph. It certainly appears that the wheel rotation frequency at 65 mph and the floating slab resonance, which was designed to be 10 Hz, are interacting to amplify vibration at this frequency. At 54 mph the wheel rotation frequency is 10 Hz. It appears that the four Group 2 trains were travelling about 10 mph less than the programmed speed of 65 mph, and that there was a strong interaction between the wheel rotation frequency and the floating slab resonance frequency. Note that the vibration at the Concord floating slab did not have the same shape peak; perhaps because there is enough separation between the design resonance frequency of 8 Hz and the 12 Hz wheel rotation frequency (normal train speed at the Concord floating slab is 65 mph).

Fig. 7. Photograph of resiliently supported half ties (LVT track) in the San Francisco Airport Extension subway.

Fig. 8. Photograph of continuous floating slab track section in the San Francisco Airport Extension subway. Because there are no gaps between the floating slab and the subway invert larger than a few inches, impact testing from the invert to the surface was not feasible for this section of track.
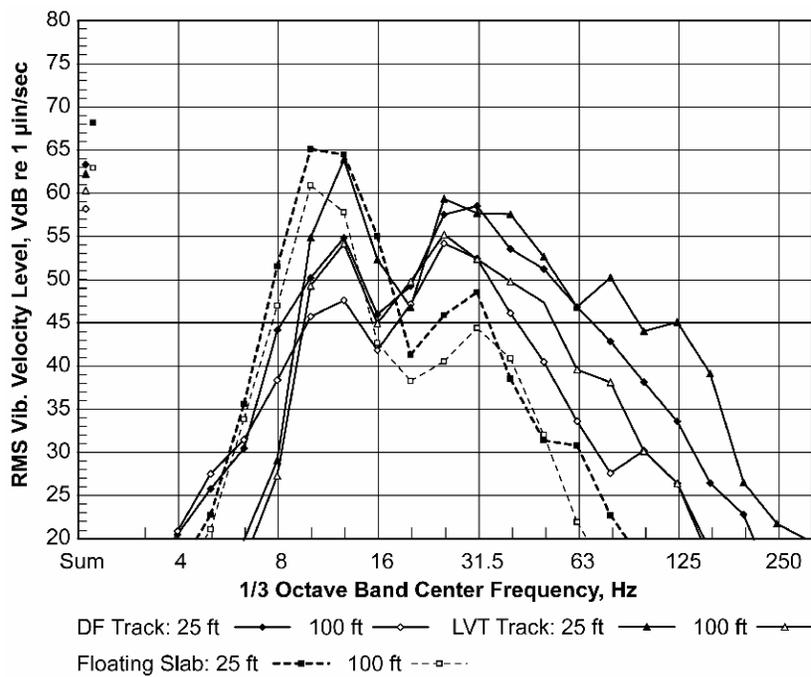

Fig. 9. Average vibration velocity levels measured at the ground surface above the San Francisco Airport Extension subway. All measurements were in the same general area of South San Francisco. Trains speeds are typically 65 mph in this area.
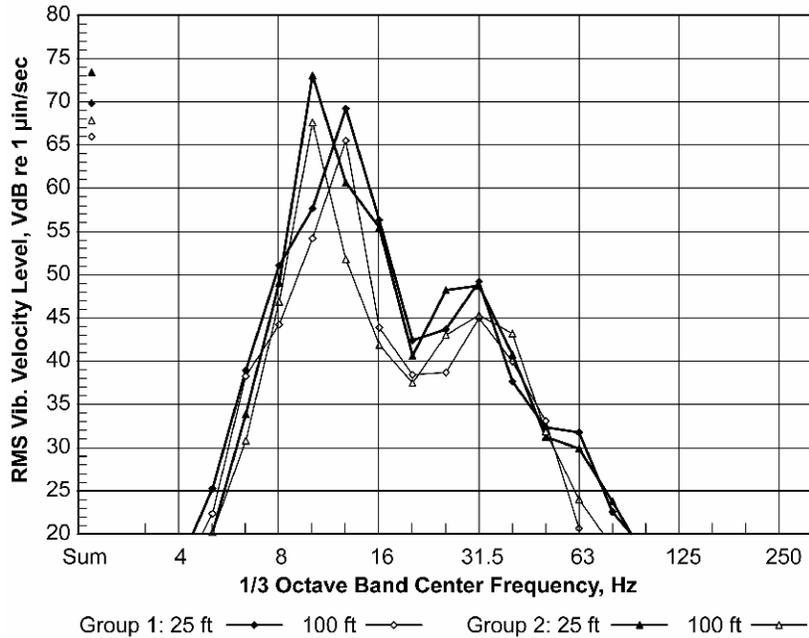
Fig. 10. Averages for two groups of trains at SFO Airport extension floating slab section.

The force densities derived for the direct fixation and LVT track in the SFO subway are shown in Fig. 11. Although there are differences of 0 to 3 dB at frequencies of 20 Hz and above, these do not look to be a consistent pattern that could be attributed to the differences in the vibration properties of the track support systems. There are 0 to 5 dB differences below 20 Hz with more vibration at LVT track between 10 and 16 Hz and less vibration at LVT track at lower frequencies. Given that there is no apparent mechanism by which the two track forms would have different low frequency vibration, we suspect that the low frequency differences are unrelated to the track fastener systems.
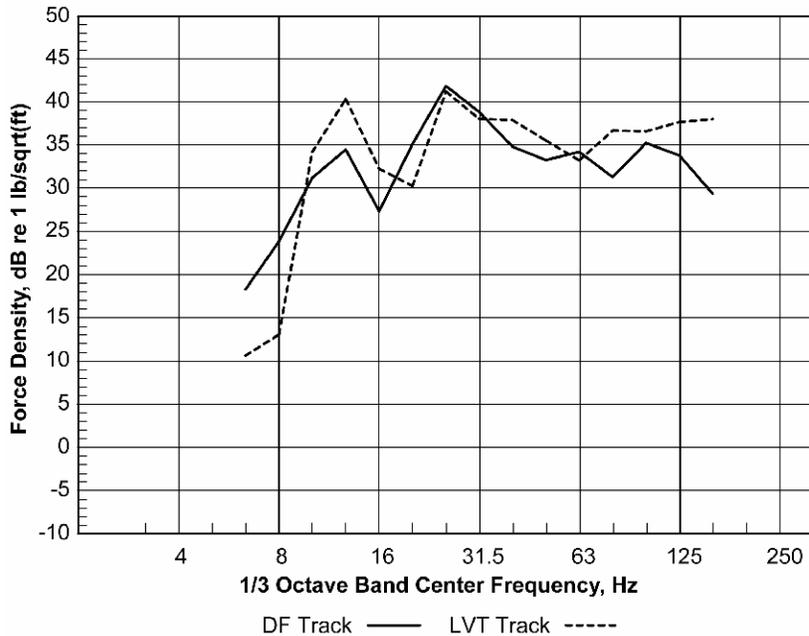

Fig. 11. Measured force density for direct fixation and LVT track, SFO Airport subway.

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The difference between the average vibration levels at the floating slab and direct fixation sections of the SFO subway are shown in Fig. 12. The fairly dramatic reduction at frequencies of 20 Hz and greater is much as expected. Note that the vibration levels at 63 Hz and above were quite low at the floating slab section and the differences at frequencies greater than 63 Hz may be understating the effectiveness of the floating slab. The strong effects of the 10 and 12 Hz peaks in the floating slab vibration spectrum are very evident in Fig. 12. It is clear from this figure that attention should be paid to the potential interaction of the wheel rotation frequency and the floating slab primary resonance when designing floating slabs.

Note that although the strong resonance effects for the SFO subway floating slab seems to be causing overall vibration levels at the floating slab track section to be *higher* than at the direct fixation sections of the SFO subway, there is no indication that this is causing objectionable vibration inside any nearby residences.
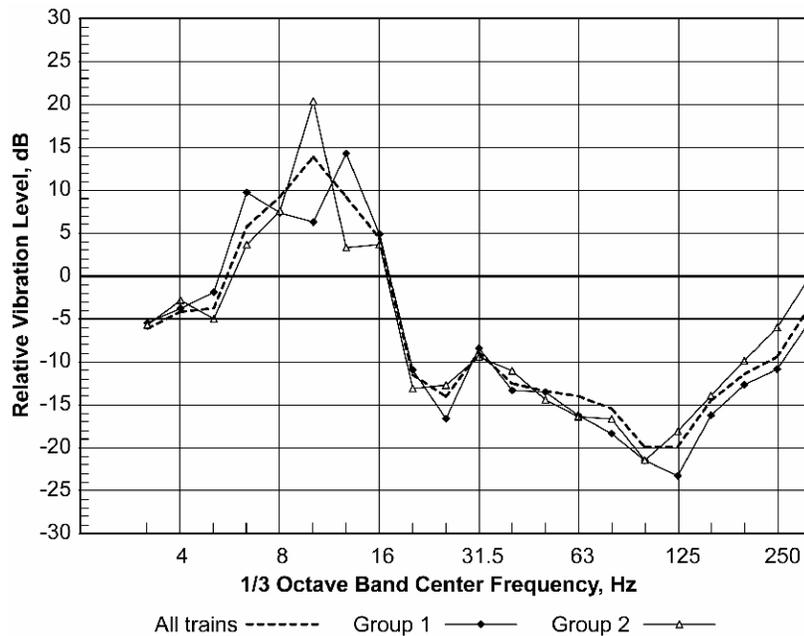

Fig. 12. Comparison of train vibration from direct fixation and floating slab test sections, SFO Airport subway. Shown are the average differences of floating slab vibration minus direct fixation vibration (a negative number implies an improvement by the floating slab).

3.3. Egg Fasteners, Balboa Park

The final track section tested is part of the original BART system in Balboa Park. BART has had ongoing problems with 1 to 2 inch wavelength rail corrugations in this area and, based on tests at other BART track sections, it was thought that use of softer direct fixation fasteners could reduce the incidence of corrugation. The vibration tests were performed at U-wall section (retained cut) just west of the portal for a roadway underpass. The original direct fixation fasteners on the inbound track had been replaced with Egg fasteners about six months before the test. The original fasteners had a stiffness of about 300k lb/inch and the new Egg fasteners have a stiffness of about 60k lb/inch.

The average vibration levels measures at two distances are shown in Fig. 13. The frequency range on this plot has been extended to 1000 Hz so that the effect of the rail corrugation can be seen. Typical corrugation wavelength at BART is 1.5 to 2 inches. At train speeds of 45 mph, this translates to a frequency of 430 to 570 Hz. The strong peak from corrugation is clear in all of the spectra in the 400 and 500 Hz 1/3 octave bands.

Because of the strong effect of the corrugation, we are hesitant to draw too many conclusions from Fig. 13 about the effectiveness of the Egg fasteners. Note that the curves for the two track sections are not directly comparable since the Eggs were on the near track and the old direct fixation fasteners were on the far track. Accounting for the track separation, it appears from Fig. 13 that that the Egg fasteners are providing 5 to 8 dB vibration attenuation at frequencies of 31.5 Hz and higher
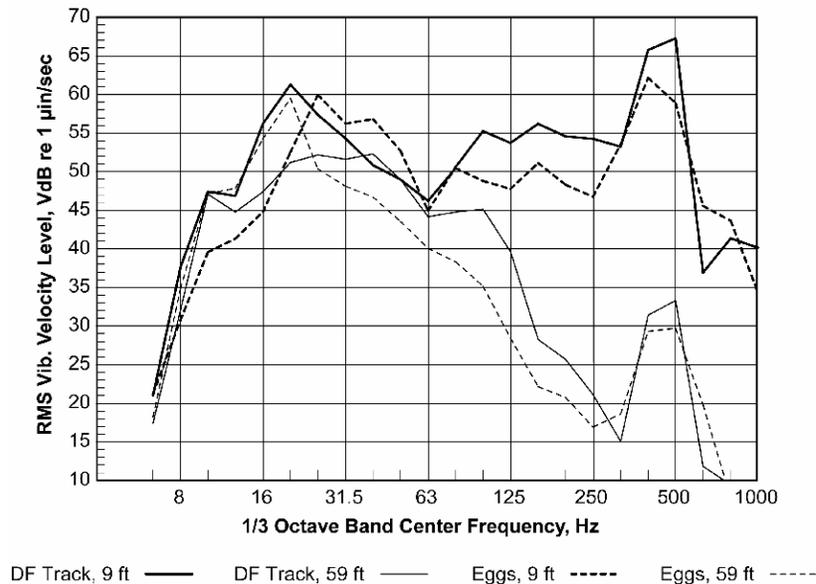

Fig. 13. Vibration at Egg resilient fastener test section, Balboa Park, average train speed = 45 mph. The distances are horizontal distance from near track centerline. The Egg fasteners were on the near track, so the actual distance to the direct fixation track is 15 ft farther than indicated above.

4. Conclusions

Our conclusions regarding the vibration mitigation measures currently in use on the BART system are:

- The floating slab track sections currently installed at BART appear to be functioning largely as designed. One potential issue is amplification when the wheel rotation frequency is close to the resonance frequency of the floating slab. At the 65 mph design speed for much of the SVRT corridor, the wheel rotation frequency is 12 Hz. The amplification was most noticeable at the SFO subway floating slab that has a design resonance frequency of 10 Hz and less noticeable at the Concord floating slab where the design resonance frequency is 8 Hz.
- The resiliently support half ties in the SFO subway (commonly called LVT track) do not appear to be providing a measurable amount of vibration mitigation compared to the standard direct fixation track in the SFO subway. The implication is that softer support pads would be needed

for the LVT track to reduce vibration relative to the standard direct fixation fasteners used in the SFO subway.

- The high-resilience Egg fasteners installed on a short section of track in the Balboa Park area may be reducing vibration levels by 5 to 8 dB at frequencies greater than 25 to 30 Hz. We suspect that some of the benefits of the Egg fasteners may be overshadowed by the rail corrugation and other factors. The rail corrugation at this site shows up as vibration in the 400 Hz and 500 Hz 1/3 octave bands, which is consistent with corrugation wavelengths of 1.5 to 2 inches and trains speeds of 45 mph. Although it is not obvious from the vibration data whether the corrugation is affecting vibration at other frequencies, there could be non-linear effects from the strong forces in the 400 to 500 Hz range that increase vibration levels at lower frequencies.

It is appropriate to make a few additional comments and observations about how these results will be applied to the SVRT project. Vibration propagation tests in the corridor using the procedures shown in Fig. 1 were performed at six representative residences. These measurements in conjunction with the force densities measured at the Hayward Test Track were used to predict future vibration levels inside living spaces of these residences. The testing confirmed that the proposed BART extension would be likely to cause vibration levels that exceed the Federal Transit Administration vibration impact threshold of 72 VdB (vibration velocity level using a decibel reference of 1 µin/sec) at many residences in the SVRT corridor. The maximum vibration velocity is projected to be in the 12 to 25 Hz range inside five of the six residences that were tested.

It does not appear feasible to provide sufficient vibration reduction in the 12 to 25 Hz frequency range using "standard" vibration mitigation measures such as ballast mats, at the six representative residences. In fact, if there is an amplification at the ballast mat resonance frequency as computer models of ballast mats usually indicate, ballast mats could even increase overall vibration levels.

Our analysis showed that, in most cases, a floating slab similar to the one in Concord with a design resonance frequency of 8 Hz should eliminate the vibration impacts. This approach could be overkill in many cases; however, it may not be feasible to know in advance whether or not an 8 Hz floating slab is needed without performing vibration tests at each residence or cluster of residences where vibration mitigation is recommended.

Similar to ballast mats, a floating slab with a design resonance of 10 Hz or greater runs the risk of increasing overall vibration levels because of interaction with the wheel rotation frequency.

Because of the dominance of the low frequencies, we did a brief evaluation of alternative methods to reduce low frequency vibrations using finite element modeling. Briefly, the conclusion was that in many cases sufficient low-frequency vibration mitigation could be achieved through a shallow pier foundation or other means of adding mass and stiffness to the track support system for at-grade ballast and tie track.

Acknowledgements

References

[1]   R. Carman, G. LaBonte, Floating Slab Trackbed Vibration, Test Results of a Full Scale Mock-Up, presented at the American Public Transportation Agency 1994 Rapid Transit Conference, June 1994.