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In-service tests of the effectiveness of vibration control measures on the BART rail transit system

Hugh Saurenman[a,*], James Phillips[b]

[a] ATS Consulting, 801, South Grand Avenue, Suite 575, Los Angeles, CA 90017, USA
[b] Wilson, Ihrig & Associates, Inc., 5776 Broadway, Oakland, CA 94618, USA

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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 to 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 bogie dynamics, and vibration propagation characteristics of the ground.

1. Introduction

The Bay Area Rapid Transit (BART) System is an approximately 120 km (75 miles) 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. When this paper was written, the SVRT project was 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.

Extensive measurements have been performed 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 (sleeper) 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 105 km/h (65 mph).

*Corresponding author. Tel.: +1 213 488 7770; fax: +1 213 488 0270.
E-mail addresses: hsaurenman@ATSConsulting.com (H. Saurenman), jphillips@wiai.com (J. Phillips).

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- 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 1.8 m (6 ft) 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 the 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 determine the true insertion loss of each mitigation measure. This is always problematical because of the difficulty of eliminating 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 excitation 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 centreline. Ground surface vibration velocity in the vertical direction was measured with a line of transducers perpendicular to the track. As indicated in Fig. 1, a similar series of tests was performed along the proposed SVRT corridor to measure transfer mobility from the track centreline into living spaces of adjacent residences. This procedure allows projected indoor vibration levels to be determined 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 transfer mobility and train vibration were measured using the same transducer locations. The vibration forces generated by the trains were then estimated using the following relationship for each one-third octave band:

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

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

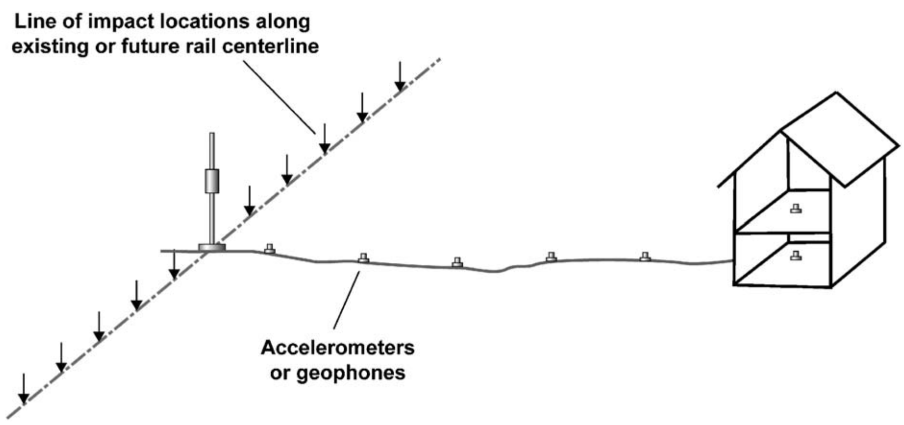


Fig. 1. Sketch of vibration propagation test procedure for at-grade track. As indicated in the sketch, additional tests were performed in the SVRT corridor from the proposed track centreline into living spaces of representative residences.

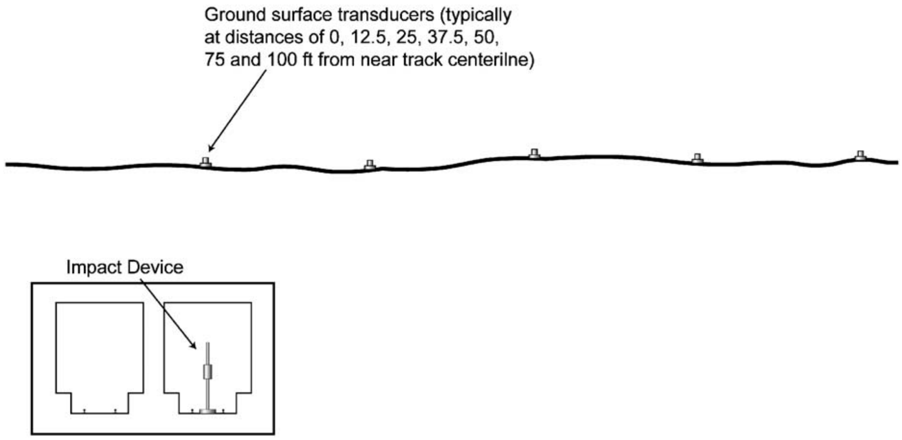


Fig. 2. Sketch of vibration propagation test procedure used for subway track sections. The measured transfer mobility is from the subway invert to the ground surface.

FDL spectrum was calculated for each transducer location and average FDL was used to characterize the track type.

3. Measurement results

3.1. At-grade track

The tests for at-grade track consisted of 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 one-third octave band spectra for three similar distances measured from the track centreline at train speeds of 105 km/h (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 of 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 slab 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 40–50 Hz, it is suspected that the curve in Fig. 6 understates the high-frequency insertion loss. Also, the positive insertion loss in the 6.3 and 8 Hz one-third octave bands results is unlikely to be correct 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.

3.2. Outdoor to indoor effects

A critical factor in predicting levels of ground-borne vibration is how the vibration changes as it propagates from the ground into the building structure and then through the building structure to living spaces. The

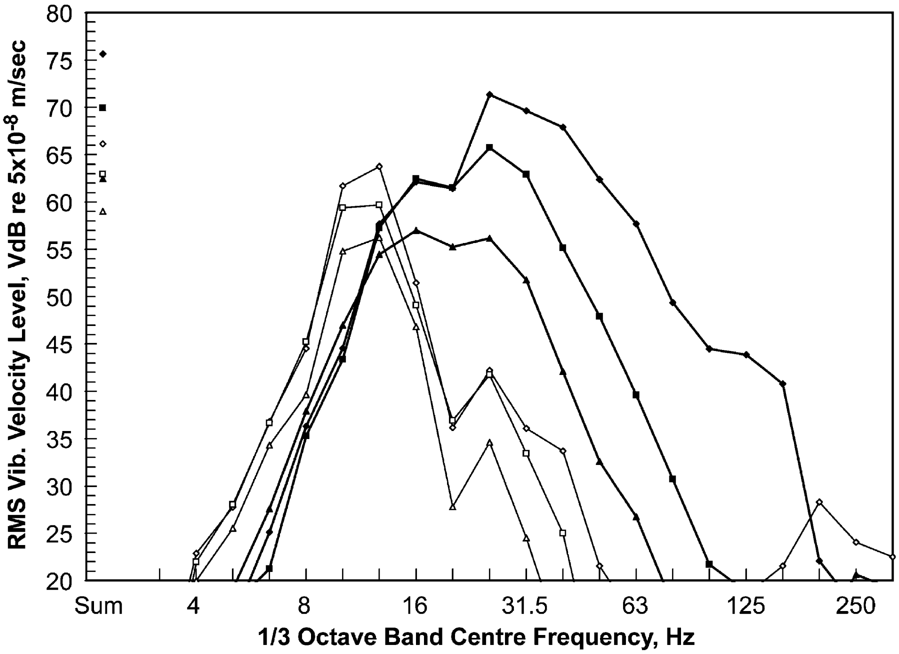


Fig. 3. Average vibration levels measured at Hayward Test Track and Concord floating slab. Average train speed was 105 km/h (65 mph) at both sites. Hayward Test Track: 8.5 m (28 ft), 17.4 m (57 ft), 32.6 m (107 ft); Concord Floating Slab: 7.6 m (25 ft), 15.2 m (50 ft), 30.5 m (100 ft).

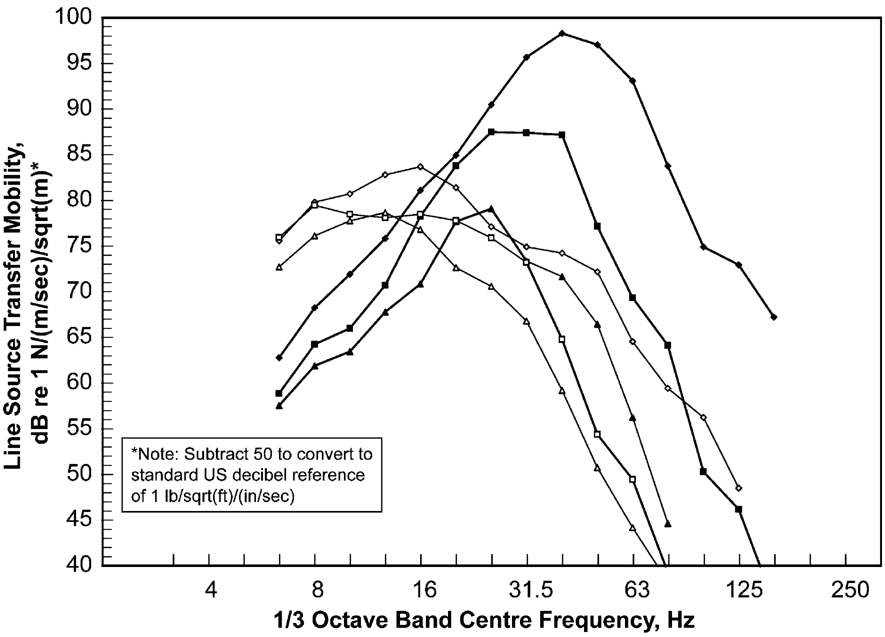


Fig. 4. Line source transfer mobilities measured at the Hayward test track and Concord floating slab test sites. Floating slab transfer mobility is from the slab foundation to the ground surface and the Hayward Test Track transfer mobility is from the toe of the ballast to the ground surface. Hence, the floating slab transfer mobility includes the effects of the concrete foundation for the floating slab. Hayward Test Track: 8.5 m (28 ft), 17.4 m (57 ft), 32.6 m (107 ft); Concord Floating Slab: 7.6 m (25 ft), 15.2 m (50 ft), 30.5 m (100 ft).

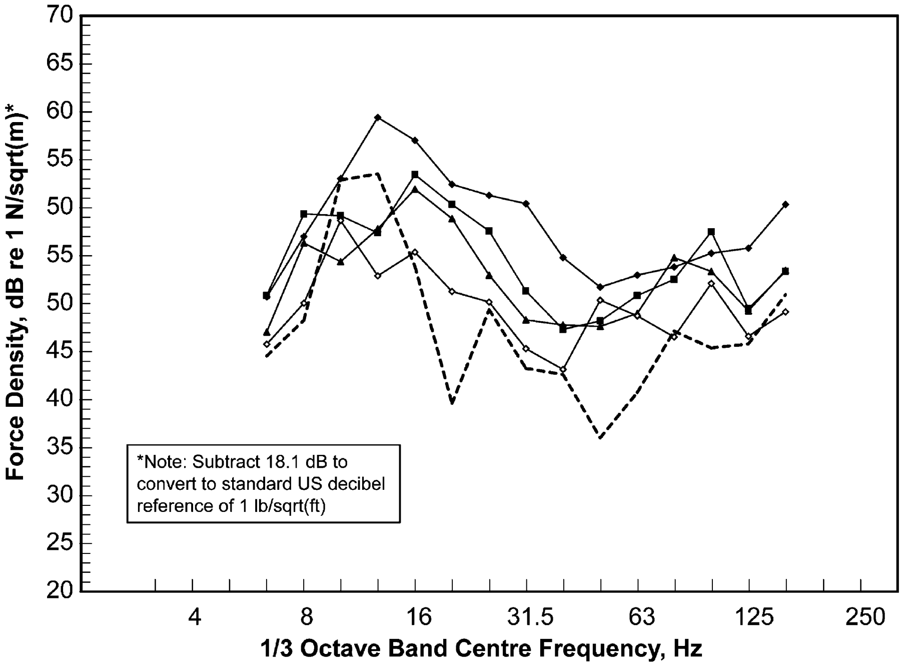


Fig. 5. Derived force densities for Hayward Test Track and Concord floating slab. Hayward Test Track: —◆— 105 kph (65 mph), —■— 64 kph (40 mph), —▲— 55 kph (34 mph), —◇— 37 kph (23 mph); Concord Floating Slab: ----- 105 kph (65 mph).

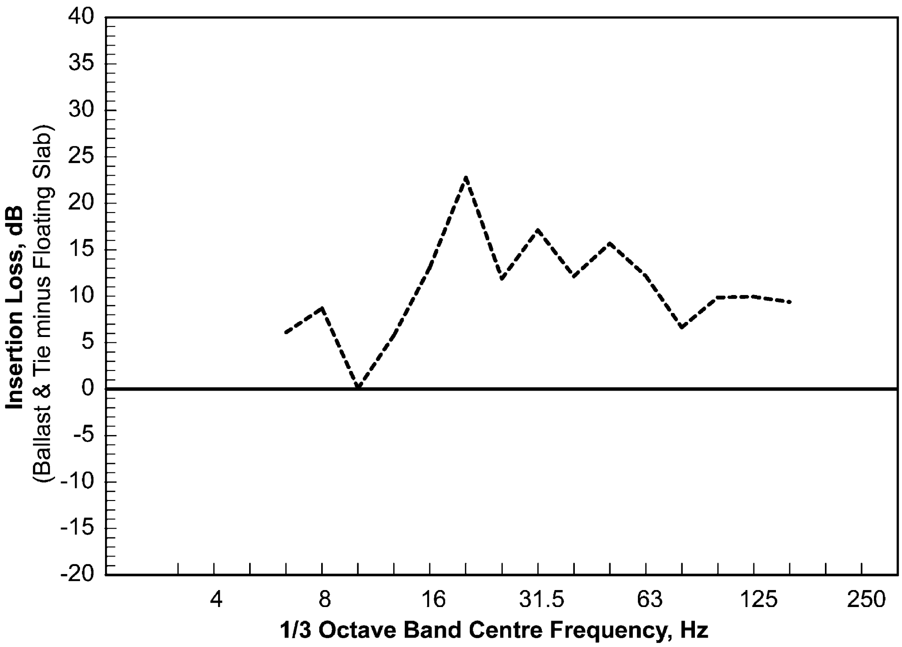


Fig. 6. Measured insertion loss for Concord floating slab compared to Hayward test track, 105 km/h (65 mph) trains (positive insertion loss indicates improvement). The values at frequencies greater than about 40–50 Hz are questionable because of the low vibration amplitudes at the floating slab test site at these frequencies.

measured indoor minus outdoor vibration for the first floor spaces of residential slab-on-grade construction is shown in Fig. 7(A). As can be seen, the indoor vibration levels tended to be less than the outdoor vibration in all the residences except at the higher frequencies that are beyond the range of importance for the SVRT corridor. On average, the indoor vibration levels in the first floor spaces were about 3 dB lower than the outdoor vibration.

The indoor vibration levels tend to be amplified on second floor and suspended first floor spaces. The results for the two rooms in the mobile home are shown in Fig. 7(B) and the second floor results for the single family and townhouse residences are shown in Fig. 7(C). It is clear that there were resonances excited in the mobile home that resulted in vibration amplification. It is interesting that the peak amplification occurred at 30 Hz in one room of the mobile home and at 50 Hz in the other room. The measurements were performed in two adjacent bedrooms. This is an indication of just how site-specific the floor amplification can be. In this case, even though measurements were in adjacent rooms and were only separated by 3–4 m, the amplification was at very different frequencies.

There also is substantial variation between the four second floor measurements (Fig. 7(C)). It may be coincidence, but the second floor vibration for the two townhouses is similar and the second floor vibration for the two single-family houses is similar. The townhouses (S2 and S5) have amplification at 25 Hz in one residence and 40 Hz in the other. In contrast, there was no little or no amplification in the second floor vibration of the two single family residences. The data in Fig. 7(C) suggest that there may be something in the construction of townhouses that tends to result in more second floor amplification than is the case for single family residences. This can be an important issue since the assumed amplification for second floor vibration can be the factor that determines whether, and how much, vibration mitigation is required.

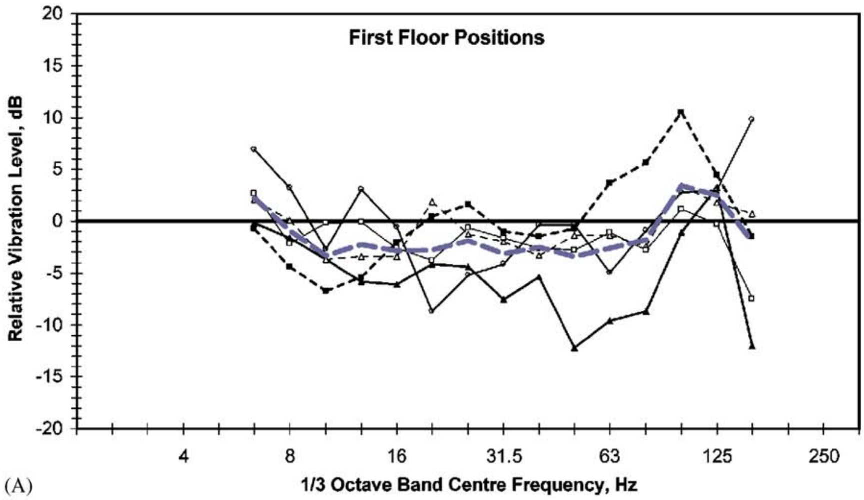
3.3. San Francisco airport extension subway

The three SFO subway test sections were located within approximately 800 m (half a mile) of each other. The subway through this area is all double-box subway of cut-and-cover construction. The track is about 9 m (30 ft) 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 26 MN/m (150 klb/in), 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. 8 is a photograph of the LVT track and Fig. 9 is a photograph of the floating slab section.

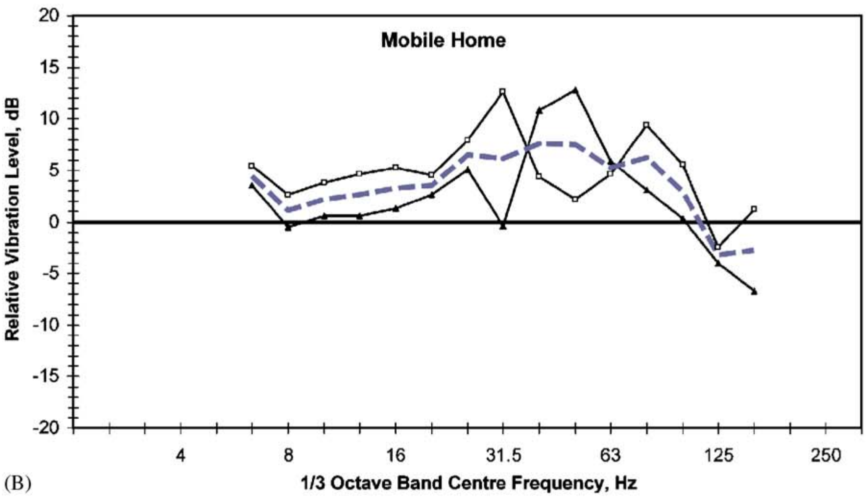
As discussed above and shown in Fig. 2, the intention was to use impact testing to measure transfer mobility from the subway invert to the ground surface at all three test sites in the SFO subway. Unfortunately, as shown in Fig. 9, the floating slab is a continuous design with no access to the invert large enough to perform impact tests. The means that a comparison of measured ground-surface vibration levels has to be used to infer how effective the floating slab is at reducing vibration levels.

Fig. 10 shows the vibration spectra measured at 7.6 m (25 ft) and 30.5 m (100 ft) from the track centreline (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, it was noted that most of the trains either had a strong peak in the 10 Hz one-third octave band or the in the 12.5 Hz one-third octave band. It is suspected 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 (12.5 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 (Fig. 11).

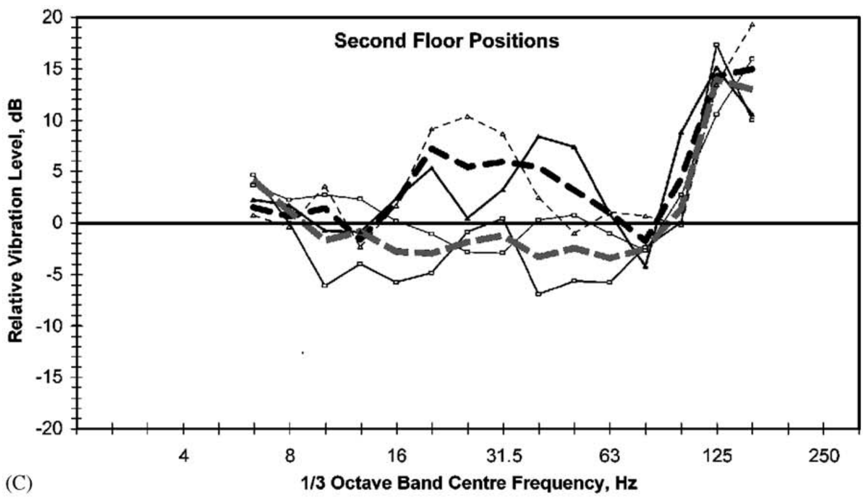
BART trains have 0.76 m (30 in) diameter wheels, which means that at 105 km/h (65 mph) the wheel rotation frequency is 12 Hz. The programmed speed for trains in the test section of the SFO subway is 105 km/h. It certainly appears that the wheel rotation frequency at 105 km/h and the floating slab resonance, which was designed to be 10 Hz, are interacting to amplify vibration at this frequency. At 87 km/h (54 mph) the wheel rotation frequency is 10 Hz. It appears that the four Group 2 trains were travelling about 16 km/h (10 mph) less than the programmed speed of 105 km/h, 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



(A)



(B)



(C)

Fig 7. Measured outdoor to indoor vibration change (indoor minus outdoor): (A) Results on first floor (ground floor) of slab on grade residential construction. S2, S3, S4, S5, S7, Average. (B) Results for two measurements inside one mobile home. Room 1, Room 2, Average. (C) Results on second floor of two-storey residences. First floor of all residences was slab on grade. S2, S3, S4, S5, S7, Avg. Townhouse, Avg. SF.

Fig. 8. Photograph of resiliently supported half-ties (LVT track) in the San Francisco Airport Extension subway.

Fig. 9. 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.

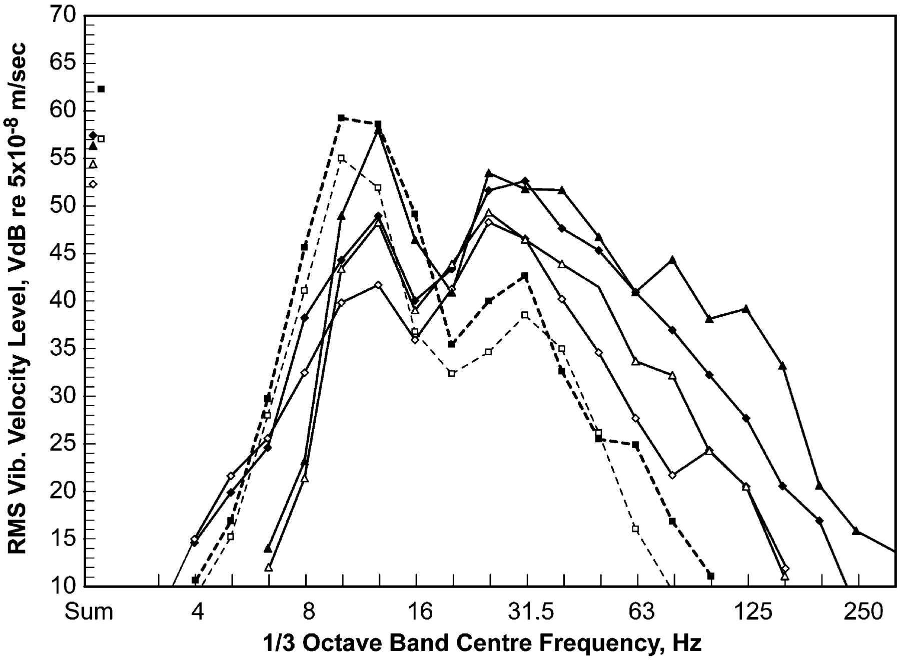


Fig. 10. Average vibration velocity levels measured at the ground surface above the San Francisco Airport Extension subway. All measurements were in the same general area of South San Francisco. Trains speeds are typically 105 km/h (65 mph) in this area. DF Track: 7.6 m (25 ft) ——, 30.5 m (100 ft) ——, Floating Slab: 7.6 m (25 ft) ——, 30.5 m (100 ft) ——, LVT Track: 7.6 m (25 ft) ——, 30.5 m (100 ft) ——.

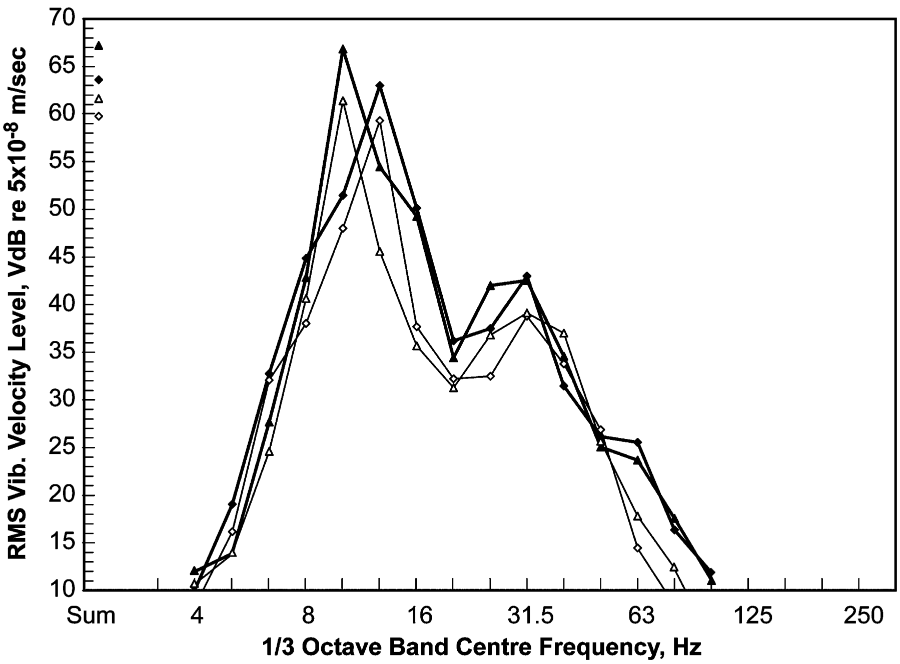


Fig. 11. Averages for two groups of trains at SFO Airport extension floating slab section. Group 1: 7.6 m (25 ft) ——, 30.5 m (100 ft) ——, Group 2: 7.6 m (25 ft) ——, 30.5 m (100 ft) ——.

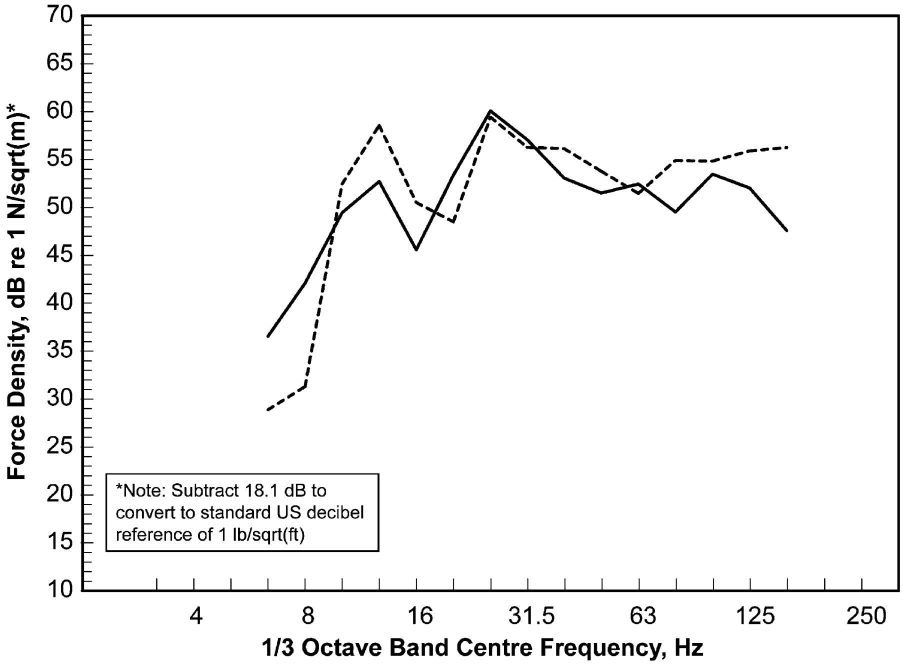


Fig. 12. Measured force density for direct fixation and LVT track, SFO Airport subway. DF Track ———, LVT Track -----.

slab did not have the same shape of 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 105 km/h).

The force densities derived for the direct fixation and LVT track in the SFO subway are shown in Fig. 12. These force densities represent the vibration forces into the subway structure as the transfer mobility was measured from the subway invert to the ground surface. Although there are differences of 0–3 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 0–5 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, it is suspected that the low-frequency differences are unrelated to the track fastener systems.

The difference between the average vibration levels at the floating slab and direct fixation sections of the SFO subway are shown in Fig. 13. 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 12.5 Hz peaks in the floating slab vibration spectrum are very evident in Fig. 13. 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.

3.4. 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 25–50 mm (1–2 in) 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

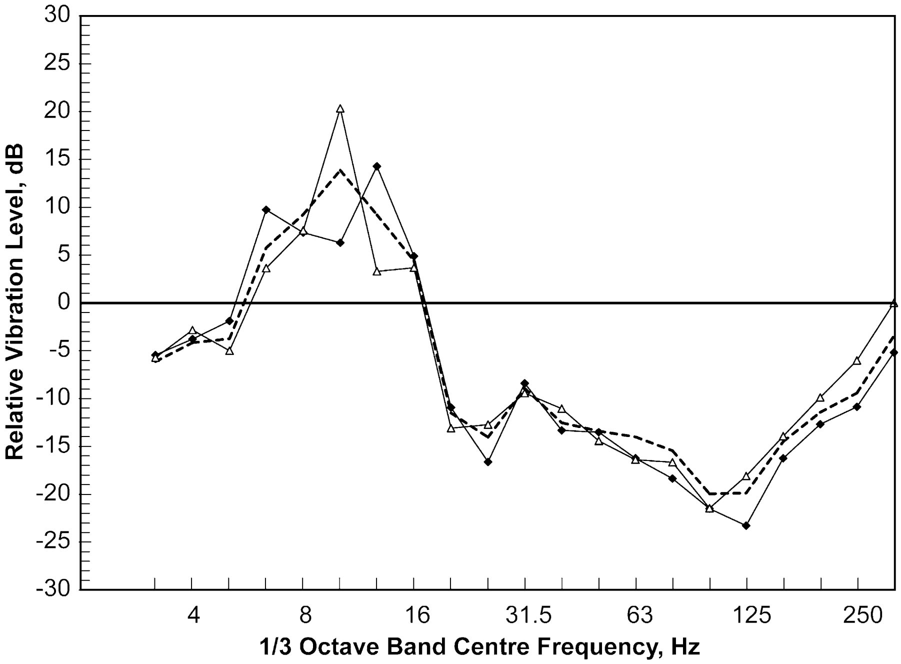


Fig. 13. Comparison of train vibration from direct fixation and floating slab test sections, SFO Airport subway. Shown are the average differences of floating slab vibration minus direct fixation vibration (a negative number implies an improvement by the floating slab). All trains - - - - -, Group 1 —◆—, Group 2 —△—.

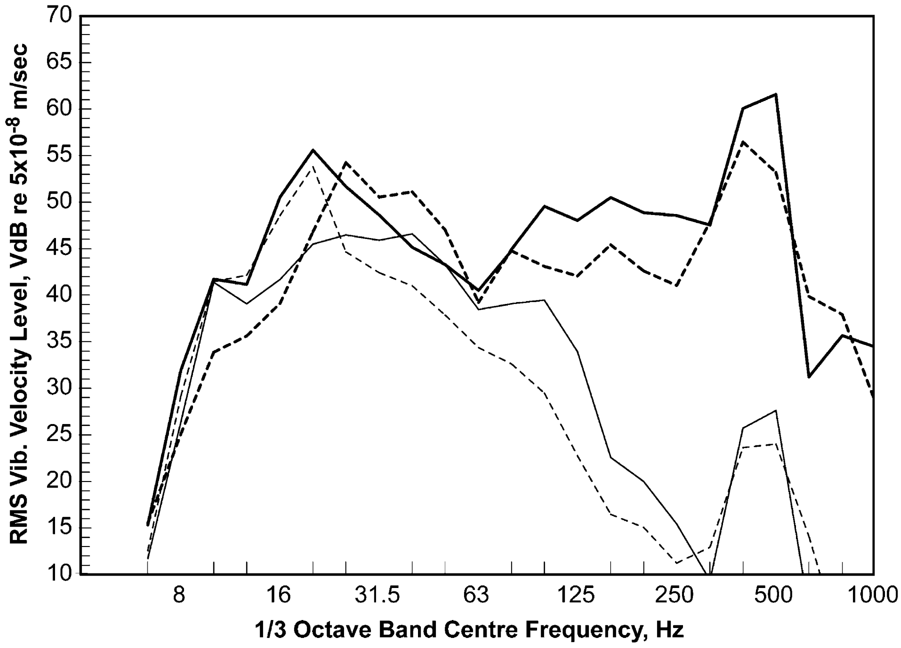


Fig. 14. Vibration at Egg resilient fastener test section, Balboa Park, average train speed 72 km/h (45 mph). The distances are horizontal distance from near track centreline. The Egg fasteners were on the near track, so the actual distance to the direct fixation track is 4.5 m (15 ft) farther than indicated above. DF Track, 2.7 m (9 ft) ——; DF Track, 18.0 m (59 ft) ——; Eggs, 2.7 m (9ft) - - - - -; Eggs, 18.0 m (59 ft) - - - - -.

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 6 months before the test. The original fasteners had a stiffness of about 52.5 MN/m (300 klb/in) and the new Egg fasteners have a stiffness of about 10.5 MN/m (60 klb/in).

The average vibration levels measures at two distances are shown in Fig. 14. 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 38–50 mm (1.5–2 in). At train speeds of 72 km/h (45 mph), this translates to a frequency of 430–570 Hz. The strong peak from corrugation is clear in all of the spectra in the 400 and 500 Hz one-third octave bands.

Because of the strong effect of the corrugation, one should be hesitant to draw too many conclusions from Fig. 14 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. 14 that that the Egg fasteners are providing 5–8 dB vibration attenuation at frequencies of 31.5 Hz and higher.

4. Conclusions

The following conclusions can be drawn regarding the vibration mitigation measures currently in use on the BART system:

- 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 105 km/h (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 supported half-ties in the SFO subway (commonly called LVT track) do not appear to be providing a measurable amount of vibration mitigation compared with 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 5–8 dB at frequencies greater than 25–30 Hz. It is suspected 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 one-third octave bands, which is consistent with corrugation wavelengths of 38–50 mm (1.5–2 in) and trains speeds of 72 km/h (45 mph). Although it is not obvious from the vibration data whether the corrugation is affecting vibration at other frequencies, there could be nonlinear effects from the strong forces in the 400–500 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 (Fig. 7). 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/s) at many residences in the SVRT corridor. The maximum vibration velocity is projected to be in the 12–25 Hz range inside five of the six residences that were tested.

It does not appear feasible to provide sufficient vibration reduction in the 12–25 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.

Analysis has shown 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, a brief evaluation has been made of alternative methods to reduce low frequency vibrations using finite element modelling. 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

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